CENTER FOR
PORTLAND CEMENT CONCRETE
PAVEMENT TECHNOLOGY

Self-Consolidating Concrete—Applications for Slip-Form Paving: Phase I (Feasibility Study)

Final Report
November 2005

IOWA STATE UNIVERSITY

This project is Federal Highway Administration Transportation Pooled Fund Study TPF-5(098)

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The Center for Portland Cement Concrete Pavement Technology (PCC Center) is housed at the Center for Transportation Research and Education (CTRE) at Iowa State University. The mission of the PCC Center is to advance the state of the art of portland cement concrete pavement technology. The center focuses on improving design, materials science, construction, and maintenance in order to produce a durable, cost-effective, sustainable pavement.

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16. Abstract

Over-consolidation is often visible as longitudinal vibrator trails in the surface of concrete pavements constructed using slip-form paving. Concrete research and practice have shown that concrete material selection and mix design can be tailored to provide a good compaction without the need for vibration. However, a challenge in developing self-consolidating concrete for slip-form paving (SF SCC) is that the new SF SCC needs to possess not only excellent self-compactibility and stability before extrusion, but also sufficient "green" strength after extrusion, while the concrete is still in a plastic state. The SF SCC to be developed will not be as fluid as the conventional SCC, but it will (1) be workable enough for machine placement, (2) be self-compacting with minimum segregation, (3) hold shape after extrusion from a paver, and (4) have performance properties (strength and durability) compatible to current pavement concrete.

The overall objective of this project is to develop a new type of SCC for slip-form paving to produce more workable concrete and smoother pavements, better consolidation of the plastic concrete, and higher rates of production. Phase I demonstrated the feasibility of designing a new type of SF SCC that can not only self-consolidate, but also have sufficient green strength. In this phase, a good balance between flowability and shape stability was achieved by adopting and modifying the mix design of self-consolidating concrete to provide a high content of fine materials in the fresh concrete. It was shown that both the addition of fine particles and the modification of the type of plasticizer significantly improve fresh concrete flowability. The mixes used in this phase were also found to have very good shape stability in the fresh state.

Phase II will focus on developing a SF SCC mix design in the lab and a performing a trial of the SF SCC in the field. Phase III will include field study, performance monitoring, and technology transfer.

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SELF-CONSOLIDATING CONCRETE—APPLICATIONS FOR SLIP-FORM PAVING: PHASE I (FEASIBILITY STUDY)

Final Report
November 2005

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1. INTRODUCTION

1.1. Problem Statement

Slip-form paving has been extensively used by the worldwide paving industry since its development in Iowa in the 1940s. Different from the fixed-form paving, slip-form paving brings together concrete placing, casting, consolidation, and finishing into one unique process. In this paving process, concrete mixture with a slump less than 2” is placed in front of a paver. As the paver moves forward, the mixture is spread, leveled, consolidated (by equally spaced internal vibrators), and then extruded. After extrusion, the fresh concrete slab can hold shape for further surface finishing, texturing, and curing until the concrete sets. Because of the low consistency of the mixture, a great deal of vibration is needed to move entrapped air and consolidate the concrete.

Over-consolidation of pavements is noted visually in finished pavements. Longitudinal trails are observed in the surface of the portland cement concrete (PCC) pavements. These trails, called vibrator trails, run parallel to each other, with spacing similar to that of the vibrators on the pavers. Cores taken from vibrator trails of some pavements have revealed that in many instances the hardened concrete contains less than 3% air, rather than 6%–7% as designed, thus significantly reducing concrete freeze-thaw durability (Tymkowicz and Steffes, 1996). Although some measures are taken to monitor the frequency of the vibrators, improper vibrations are sometime still inevitable. It would be a revolutionary advance in paving technology if vibration of pavement concrete can be eliminated.

Today’s concrete research and practice have shown that material selection and mix design of concrete can be tailored to provide a good compaction without the need for vibration. This approach is based on the principles of self-consolidating concrete (SCC) widely used in precast and cast-in-place construction. SCC has generated tremendous industrial interest since its initial introduction in Japan (1990). Due to its excellent flowability and stability (segregation resistance), SCC has been used for many different applications, including bridge decks, precast bridge members, and pavement repairs. SCC can be cast and self-consolidated in small dimension and/or heavily reinforced formwork without vibration. Use of SCC technology also increases the speed of the construction, improves the quality of the concrete (without segregation and loss of air), and reduces the cost of labor, energy, and environmental impacts caused by vibration and/or noise.

A challenge in developing SCC for slip-form paving (SF SCC) is that the new SF SCC needs to possess not only excellent self-compactibility and stability before extrusion but also sufficient “green” strength right after extrusion while the concrete is still in a plastic (green) state. Such green strength will ensure that the fresh concrete can sustain its self-weight, or holds the slab in shape, without having support from any framework. It is understood that to obtain self-compactibility, a concrete mixture needs to overcome the shear strength resulting primarily from particle friction and cohesion; in order to hold the slab in shape, the fresh concrete must gain certain shear strength. A key issue is how to achieve these two conflicting needs for concrete at the appropriate time.

Concrete is a thixotropic material. At a high shear rate (such as during mixing), concrete microstructure is disturbed, and its yield stress and viscosity are reduced. Thus, the concrete becomes more flowable and self-compactible. While at a low (or zero) shear rate, concrete microstructure can be re-built, green strength will develop, and the concrete becomes less deformable. The extrusion process, even at a low pressure, will help concrete consolidation, while thixotropy will lead to green strength development by rearranging solid particles for packing.

Based on the current knowledge of concrete materials, the project investigators believe that a rational balance between compactibility and green strength or shape-holding ability of a concrete mixture may be timely achieved by tailoring concrete materials and mix design. This represents great potential for development of a desirable SF SCC. The new SF SCC is not as fluid as the conventional SCC, but it will (1) be workable enough for machine placement, (2) be self-compacting with minimum segregation, (3) hold shape after extrusion from a paver, and (4) have compatible performance properties (strength and durability) to the current pavement concrete.

1.2. Overall Project Objectives

The overall goal of the Self-Consolidating Concrete—Applications for Slip-Form Paving project is to develop a new type of SCC for slip-form paving. Specific project objectives include the following:

- Simulate the slip-form paving process in laboratory.
- Explore test methods that can appropriately measure the characteristics of SF SCC.
- Investigate essential paste material components (such as superplasticizer, viscosity modifying agent [VMA], mineral filler, and other new admixtures) and their roles in SF SCC.
- Study the effects of particle packing and orientation on the properties of SF SCC.
- Develop mix design methodology, acceptance criteria, and mix proportions for SF SCC.
- Conduct a preliminary field investigation for new SF SCC mixes.
- Evaluate the properties of field SF SCC.

1.3. Overview of Project Phases

This project consists of three phases:

- Phase I: Feasibility Study. The main task of this phase (documented in this report) was to demonstrate the feasibility for designing a new type of SF SCC that can not only self-consolidate but also have timely shape-holding ability.
- Phase II: Mix Design Refinement and Field Trial Testing of SF SCC. After achieving positive results from Phase I, the Phase II study is to further develop mix design methodology and acceptance criteria for SF SCC made with various concrete materials. A trial of the SF SCC mix design will be performed in the field.
- Phase IIIA: Field Investigation of SF SCC Paving. The Phase IIIA study will be conducted to implement the Phase II research results in field.

- Phase IIIB: Performance Monitoring and Technology Transfer. The Phase IIIB study will monitor the performance of the SF SCC pavement sections at 1, 3, and 5 year intervals.

1.4. Phase I Tasks

Phase I tasks included the following:

- Form an industrial advisory panel for the project and collected industrial input on the new technology.
- Investigate essential material components and potential mix proportions of SF SCC.
- Develop test methods for characterization of the new SF SCC.
- Simulate the slip-form paving process in laboratory.

1.5. Phase I Background and Oversight

The project started with a kickoff meeting at Crowne Plaza, Holiday Inn, O'Hare Airport, Chicago, on September 14, 2004. The following 13 people attended the meeting:

- John Mullarky, Office of Pavement Technology, Federal Highway Administration (FHWA)
- Max Grogg, FHWA–Iowa Division
- Rick Barezinsky, Kansas Department of Transportation
- Julian Bendana, New York State Department of Transportation
- James Berger, Iowa Department of Transportation
- Lieska Halsey, Nebraska Department of Roads
- Chuck Cornman, W. R. Grace
- Lionel Lemay, National Ready-Mix Cement Association
- Bob Purcell, Active Minerals
- Tom Cackler, PCC Center
- Kejin Wang, PCC Center
- Surendra Shah, ACBM
- Yilmaz Akkaya, ACBM

At the meeting, John Mullarky of the FHWA delivered a speech titled "Ideas, Opportunities, and Challenges for Self-Consolidating Concrete in Highway Applications." Summarizing the ACBM research on SCC and extrusion, Surendra Shah and Yilmaz Akkaya addressed "Improved Processing for Sip-Form Paving Applications." Tom Cackler and Kejin Wang of the PCC Center briefed the audience about the SF SCC project and its initial research plan.

Roundtable discussions on broad issues of the SF SCC project followed. The specific question topics were discussed:

- What is happening in the current slip form paving process—extrusion or not?
- What kinds of materials should be considered in the SF SCC mixture development—aggregate type and quality, supplementary cementitious, and chemical admixtures?

- Will we be looking at constructability issues related to environmental conditions?
- Should we consider cost as an important factor for the new SF SCC development?
- What else can the new SF SCC benefit the concrete paving industry besides minimizing vibration?

Valuable input on the need for, importance of, and concern about the new SF SCC as well as information on the current practice of conventional SCC and slip-form paving were provided by the participants.

Considering all the input and prioritizing possible research activities, the research team set its goal for the Phase I study, which was approved by all the meeting participants: “At the end of Phase I, the research team will achieve one or more mix designs for new SF SCC that shall have the same shape-holding ability and hardened strength as current slip-form pavement concrete mixes.” The research team envisioned that the new SF SCC would produce more workable, uniform, and durable concrete and smother pavements with a higher production rate. Besides use in regular slip-form paving, the new SF SCC can also be applied in ultra-thin overlays, two-lift paving, and curb constructions.

At the end of the meeting, the project Industrial Advisory Panel (IAP) was formed. The panel consisted of the members from FHWA, DOTs, and concrete material/admixture suppliers who attended the meeting.

1.6. Summary of Iowa State University Work

The research team first investigated the effects of materials on concrete flowability, consolidation, and shape-hold ability. The investigation at the PCC Center was focused on the effects of supplementary cementitious materials (SCMs) (such as slag, fly ash, limestone dust, gypsum, and Acti-gel) and aggregate gradation on flow behavior of pastes and concrete. The flow properties of pastes were evaluated by a Brookfield rheometer, and the flow properties of concrete were primarily assessed by a standard slump cone test.

The researchers found that (1) slag replacement increased both yield stress and viscosity, while fly ash replacement decreased yield stress but increased the viscosity of paste, the later of which provided the paste with a better flow; (2) quality of coarse aggregate gradation could be evaluated with the difference between loose and compacted bulk density of the aggregate, which provided a good indication of the energy needed for the aggregate to be well packed and had a close relationship with concrete compaction factor; and (3) concrete mixtures made with different materials and mix proportions displayed different slump, spread, and shape after slump cone tests. Some concrete mixtures may have a similar slump value but different spread values and shape stability.

Conventional pavement concrete mixtures (such as Iowa DOT C3 mix) had a low slump and very little spread. This concrete showed good shape-holding ability but little flowability without vibration. On the other hand, conventional SCC had very high slump and large spread values. This concrete flowed well but had no timely shape-holding ability, therefore requiring formwork for construction. The researchers found out that the flow behavior of the new SF SCC is between these two extreme concrete mixtures (i.e., conventional pavement concrete and SCC mixtures).

The shape of the concrete after the slump cone test could also provide valuable information on the shape-holding ability of the concrete. Several mixtures tested at ISU had similar slump but only a few mixtures kept a regular short cone shape after the slump cone was removed. The researchers identified that the potential new SF SCC mixtures might have a slump value of approximate 8” and a spread value of approximate 13”–15” with a regular short cone shape after the slump cone was removed.

After identifying the features of the potential SF SCC mixtures, the researchers at ISU then developed a simple test method to evaluate the green strength of the concrete mixtures. In this simple test, a fresh concrete cylinder sample was loaded slowly with sand until it collapsed. The total amount of sand applied in the test divided by the loading area of the sample defined the green strength of the concrete. Researchers found that the green strength generally decreased with concrete compaction factor. The green strength of the potential SF SCC developed at ISU (cast with no additional consolidation) was only a third of that of conventional pavement concrete (C3 mixture, cast with rodding). Although having low green strength, the potential SF SCC did self-consolidate and held its shape very well right after casting and de-molding. Addition of Acti-gel into the SF SCC mixture could significantly increase the concrete green strength. Adopting this simple test method, the ACBM researchers had further evaluated green strength of various concrete mixtures.

Three months after starting the research project (December 2004), the research team (PCC Center and ACBM) reported these initial research results to the IAP members through email. The presentation slides sent via email clearly demonstrated the high possibility for developing a new type of SF SCC mixture that can self-consolidate and hold its shape right after casting and de-molding. The 7-day compressive strength of the new SF SCC cylinder samples was approximate 5500 psi, comparable with that of conventional pavement concrete. Digital images were taken from the cross sections of the hardened SF SCC cylinder samples, and they illustrated no visible honeycombing or segregation in the SF SCC. Encouraged by the initial success, the project team was eager to find out whether or not this new SF SCC was applicable to field paving. To address this question, the project team shifted the research focus from the SF SCC mix design study and green strength measurements into the lab simulation of the slip-form paving process.

With broad experience in the field concrete paving, the research team members at ISU developed a simple mini-paver for paving SF SCC segments in the laboratory. Considering that SF SCC might need a certain pressure to consolidate, the mini-paver was designed based on an L-box concept. Right before paving, concrete was stored on the platform, and approximately 200 pound of weight was placed on the back of the paver (in a chamber). To start paving, concrete was pushed from the platform into the vertical leg of the L-box up to a certain height, which generated a pressure to consolidate the concrete. Then, the mini-paver was pulled forward by a crank system at a designed speed (3–5 ft/min). As the mini-paver moved forward, it extruded the concrete, or a pavement slab, out of the horizontal leg of the L-box.

In April 2005, the first trial of the mini-paver test was conducted at ISU's PCC Pavement and Materials Research Laboratory. Using a new SF SCC mixture and the newly developed mini-paver equipment, the researchers paved a 4.5 feet of concrete slab section. With no additional consolidation applied during the test, the SF SCC not only flowed and consolidated well but also held the shape of the slab very well, especially at edge. On the very next day, the slab section was sawed into three pieces, and the cross section of the slab was examined. Again, there was neither visible honeycombing nor segregation. Cores (2"x4") were taken from the slab at the age of 9 days. The compressive strength of the cores was 4900 psi and the tensile strength was 420 psi.

On May 6, 2005, PCC Center and ACBM team members met at ISU. Together, they conducted a teleconference with all the IAP members. Twenty-one people participated in the teleconference. After receiving the brief presentations given by the ACBM and PCC Center members and reviewing the video tape of the mini-paver test on the project website, all participants agreed that the initial work presented by the research team had demonstrated a promising approach to further development of SF SCC for field applications. Various suggestions were provided by the participants on further study of SF SCC. These suggestions were divided into two categories: (1) for immediate action and (2) for future study.

The immediate action items suggested by the IAP members included the following:

- Conduct a mini-paver test with different sizes of dowel bars in the slab.
- Perform a mini-paver test using one or two ACBM mix proportions.
- Conduct some engineering property tests (such as set time, heat of cement hydration, and strength development) for the newly developed SF SCC.
- Summarize the Phase I study.
- Develop a proposal for Phase II/III study.

The research team has taken actions on all these suggested items. The recent mini-paver tests indicated that the SF SCC had comparable set time, heat evolution, and strength development to conventional pavement concrete. It also had a very good bond with simulated dowel bars. The selected ACBM mixture demonstrated excellent consolidation and shape-holding ability. ACBM is currently making a copy of the mini-paver equipment to simulate the slip-form paving process at its lab for more concrete mixes.

1.7. Summary of Northwestern University Work

While the PCC Center's researchers were working on the green strength test method and mini-paver development, the ACBM researchers conducted a focused, systematical investigation on the effects of mineral and chemical additives (clay, fly ash, and superplasticizer) on the flowability of fresh concrete mixtures. Specifically, the following parameters were examined:

- Type and content of plasticizer
- Paste content
- Type and content of clay
- Fly ash addition

The investigations were conducted by adapting the mixture proportion of a conventional SCC. It was then examined how the flowability of this concrete could be manipulated to combine the good flow properties with the shape stability required for concretes used for slip-form paving. An important aspect in the evaluation of the results was achieving an understanding of the relationship between green strength and flowability of the fresh concrete. The ultimate goal of the investigations is to find the optimum combination of these two parameters to achieve a self-consolidating and at the same time shape-stable material.

To investigate the influence of the type of plasticizer on the flowability and green strength of fresh concrete, the flowability of a conventional SCC mix design with a polycarboxylate-based plasticizer in different contents was compared with the same concrete mixture containing naphtaline-based plasticizer. It was found that the concrete containing naphtaline-based plasticizer exhibits a larger flow diameter on the drop table than the one containing polycarboxylate-based plasticizer. This indicates that naphtaline-based plasticizers have a positive effect on the flowability of concrete under the influence of external compaction energy.

Experiments concerning the influence of different fine materials on the flowability of fresh concrete showed that all tested clays, especially Acti-Gel, had a very high effectiveness in affecting (reducing) the flowability of the concrete. This high effectiveness was most likely due to the finer particle size of the clays compared to that of fly ash and cement powder. This motivated a more systematic investigation of the different clays. The results of this investigation are summarized in Table 1.1.

Table 1.1. Influence of Clay Type on Flowability of Fresh Concrete

Clay Type	Most beneficial additive amount (per cement weight)	Comment
Acti-Gel	1%–2%	1% represents best compromise between flow and green strength
Metakaolinite	1.5%	Increased flow by maintaining green strength of comparable plain concrete mixture
Kaolinite	1.5%	Significant increase in green strength with only minimal reduction of flow when compared to plain concrete

With respect to flowability only, the replacement is most beneficial for the amount of 10% of original cement weight. This, however, has a detrimental effect on the green strength and the shape stability of the fresh concrete. Although no green strength could be measured, the concrete did show certain shape retention. Future work will be done to improve the shape stability of this particular mixture.

The analysis of the relationship between green strength and flowability for all tested mixtures showed that the majority of the mixtures followed one main trend: green strength increased with a decrease in flow diameter after 25 drops on the drop table. An important finding is that certain mixtures were not part of this trend. These mixtures showed a higher green strength (corresponding to a better shape stability) for a given flowability than other mixtures. These mixtures are potential candidates to be recommended for use in low compaction energy concrete.

1.8. Summary of X-Ray CT Test Scan Work

X-ray computed tomography (X-ray CT) tests were performed to monitor aggregate segregation and void distribution in selected SF SCC cylinder samples. The results indicated that there was a lack of large aggregate particles in the top central portion of two of the three cylinder samples analyzed. Although no visible segregation was observed in the concrete slab, possible non-homogenous distribution of material phases in the cylinder samples may exist due to settlement over time and segregation. Further study is necessary on SF SCC segregation resistance.

2. IOWA STATE UNIVERSITY WORK

2.1. Introduction

The goal of this research project is to develop a type of concrete that can be used for slip form paving without the need for vibration. It is believed that such a new type of concrete can be designed based on the general concept of conventional self-consolidating concrete. A challenge in developing such an SCC for slip form paving (SF SCC) is that the new self-consolidating concrete needs to possess not only excellent self-compactibility and stability, but also sufficient strength while the concrete is in a plastic, or “green,” state. This green strength will ensure that the fresh concrete can sustain its own weight or hold the slab shape without support from any framework. It is understood that to obtain self-compaction, a concrete mixture needs to overcome the shear strength resulting primarily from particle friction and cohesion; however, in order to hold the shape immediately after the concrete slab is extruded from a paver, the fresh concrete must gain sufficient shear strength quickly. A key issue is to achieve these two conflicting needs at the same time, or at an appropriate time. Phase I of this project will determine whether the development of SF SCC is feasible.

To reach this research goal, the Iowa State University (ISU) research team approached the Phase I study in four steps: (1) investigate potential concrete materials and mix designs for SF SCC, (2) develop a simple test method for evaluating concrete green strength, (3) simulate the field paving process in the lab to prove the potential SF SCC mix design, and (4) perform preliminary tests for selected engineering properties of the potential SF SCC mixes. The detailed research activities in each step are described in the following sections.

2.2. Investigation of Potential Concrete Materials and Mix Design for SF SCC

2.2.1. Research Approach

The investigation of the SF SCC mix design started from a re-evaluation of conventional SCC and current pavement concrete. Conventional SCC can self-consolidate under its own weight due to its excellent flowability. The flowability of concrete is commonly measured by a standard slump cone test (ASTM 143). The slump cone test can provide two parameters: slump and spread (or slump flow) as shown in Figure 2.1. During the slump cone test, conventional SCC generally has a shape like a big pancake; therefore, its flowability is often described by spread (the diameter of the pancake) rather than slump. The spread of SCC measured from a slump cone test typically ranges from 18 to 32 inches (46 to 81 cm). With a very high slump and a large spread, conventional SCC can flow well and self-consolidate, but it has no timely shape-holding ability. Therefore, it requires formwork for construction.

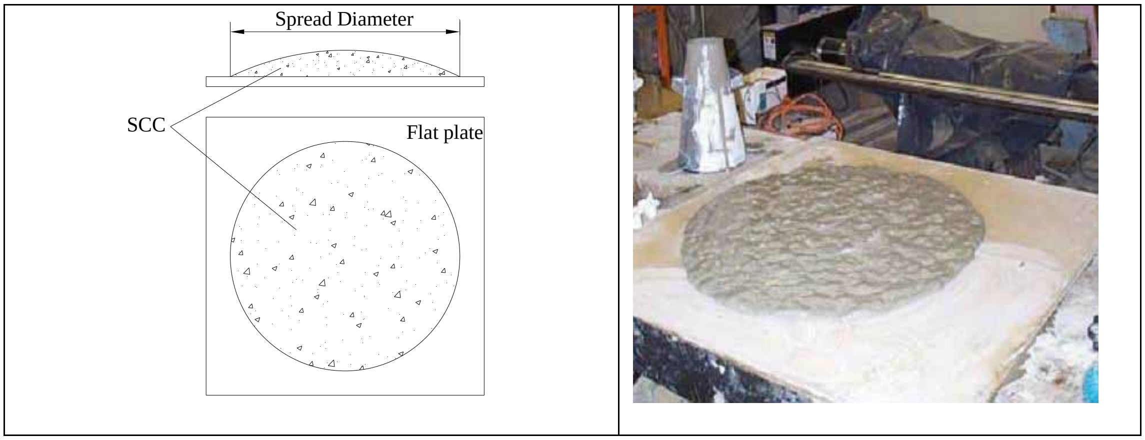


Figure 2.1. Slump flow test results for SCC

Almost every ingredient in concrete (aggregate, cementitious materials, or admixtures, and their properties and proportion) influences concrete flow ability. To achieve excellent flowability without segregation, small-sized and well-graded aggregate, supplementary cementitious materials (SCMs) (e.g., slag, fly ash, and silica fume), a water reducer or super-plasticizer, and viscosity modifying agents (VMA) are often used in conventional SCC. The principle for conventional SCC mix design is illustrated in Figure 2.2 (Ouchi et al. 1997; Sedran and Larrard 1999; Saak et al. 1998).

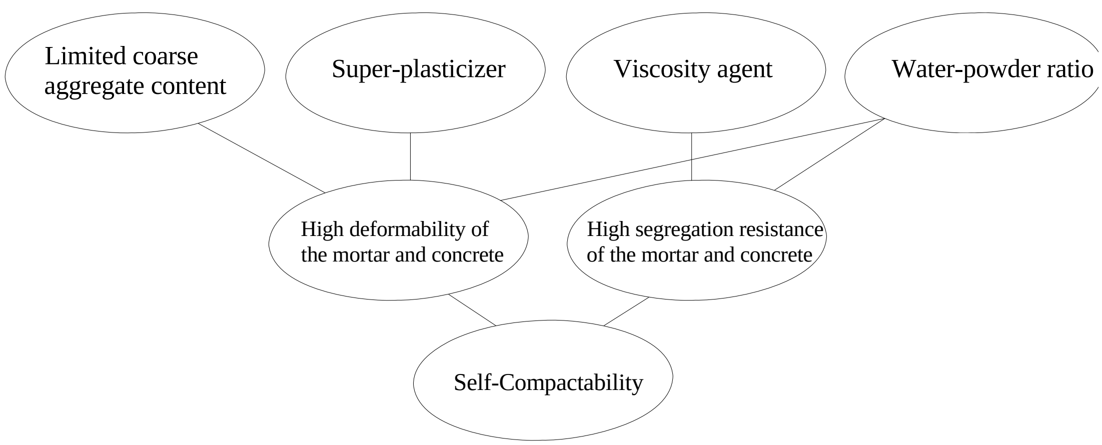


Figure 2.2. Basic principle for conventional SCC mix design

Unlike SCC, conventional pavement concrete (such as Iowa DOT C3 mix) often has a low slump (1–2 in. or 2.5–5.0 cm) and very little or no increased spread. See Figure 2.3. This concrete generally has relatively large aggregate size (1 in. or 25 mm NMSA) and good aggregate gradation, with or without SCMs and/or chemical admixtures. This concrete shows good shape-holding ability, but has little flow ability without vibration. The researchers consider that aggregate size and gradation have significant influences on particle packing and the friction between the aggregate particles and play an important role in concrete green strength or the development of shape-holding ability.

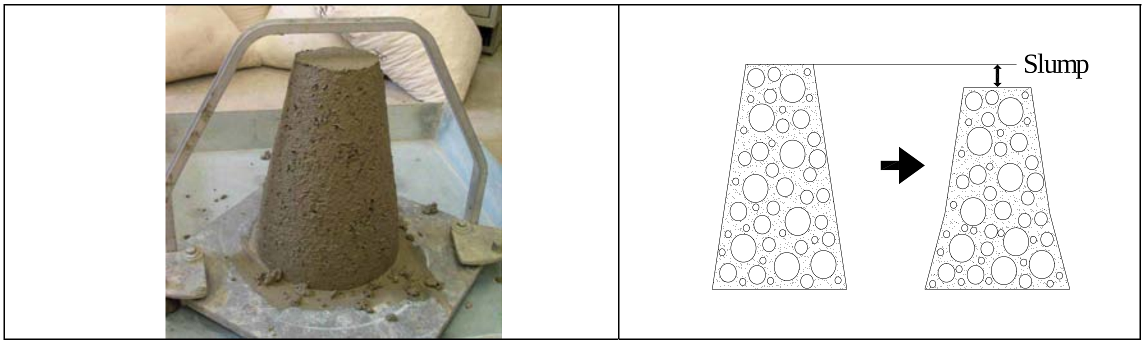


Figure 2.3. Slump cone test results for conventional slip form concrete

Models for the slump cone test process have been developed by several researchers (Christensen 1991; Schowalter and Christensen 1998), which relate the slump cone test results (slump, spread, and shape) to concrete material properties (flow ability and compactibility). Based on these research results, the following observations can be made when fresh concrete is placed into the slump cone from a constant height without any tamping, rodding, or vibration:

- If a concrete mixture has good compactibility and is well compacted, the shape or deformation of the mixture after the slump cone is removed should be plastically isotropic, as shown in Figure 2.4 (a). The mixture has a uniform aggregate particle distribution and good cohesion.
- If a concrete mixture has no good compactibility or is not well compacted, the shape or deformation of the mixture may be irregular after the slump cone is removed, due to the weak zones in the fresh concrete, as shown in Figure 2.4 (b).

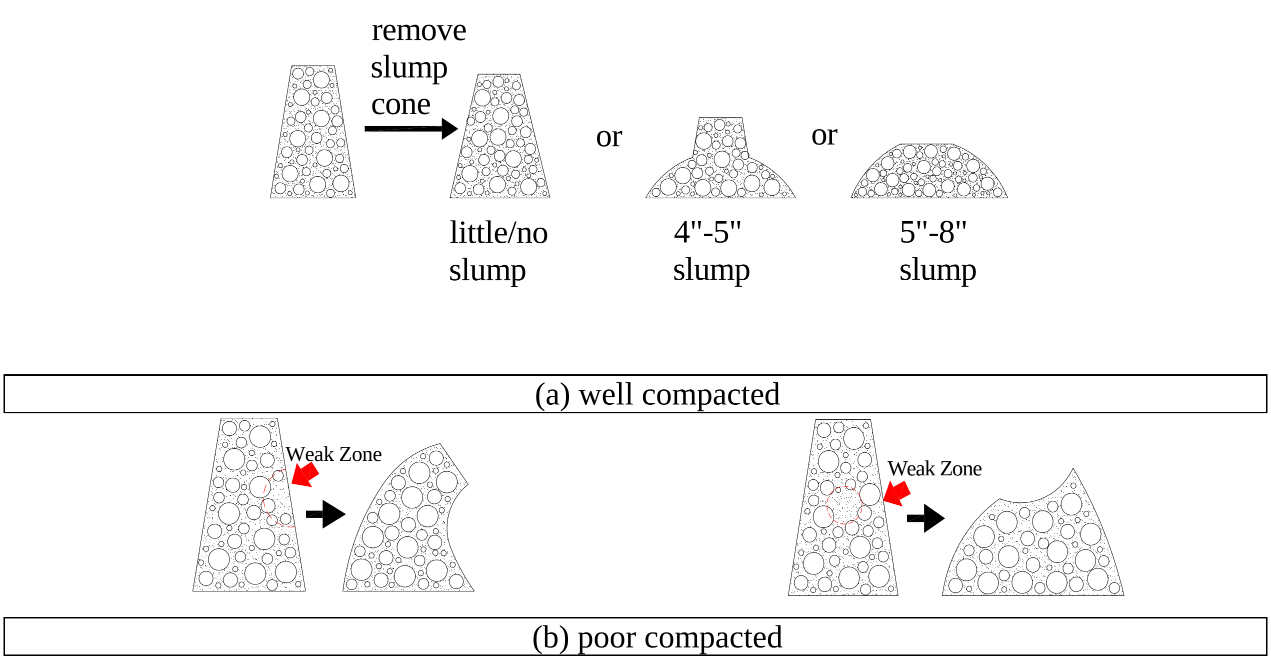


Figure 2.4. Slump cone shape versus concrete compactibility

The investigators presumed that the flow behavior of the new SF SCC should be between the two extreme concrete mixtures (conventional pavement concrete and SCC mixtures). That is, the concrete mixture should have certain slump and spread values to be able to deform or flow, and it should also have a shape or deformation after the slump cone is removed, as shown in Figure 2.4 (a), to able to be well compacted. These three slump cone test parameters (slump, spread, and shape) were used for the initial evaluation of the SF SCC mix design in the Phase I study.

To achieve the mix design objective above, the investigators first studied the effects of SCMs and admixtures on paste rheology. The study of SCMs and admixtures concentrated on fly ash, VMA, and Acti-gel. In addition, the effects of slag, limestone dust, and gypsum on paste rheology were also explored. After obtaining optimal pastes, the investigators then examined the effects of aggregate on concrete flow ability, consolidation, and shape-holding ability. The aggregate type, size, and gradations were considered. Table 2.1 describes all materials used at ISU in the Phase I study.

Table 2.1. Concrete materials and descriptions

Material	Description
Cement	Lafarge Type I
SCM	Class C fly ash from ISG Resources and Class F fly ash from Hatfield, slag from Holcim, limestone from Ames
Coarse aggregate (CA)	1-in. or 25-mm NMSA limestone with specific gravity of 2.65 (All aggregate was recombined based on the Iowa DOT C3 mix requirements and prepared to reach SSD condition before concrete casting.)
Fine aggregate (FA)	River sand with a specific gravity of 2.70, a fineness modulus of 3.1, and absorption of 1.2%
Water	Tap water
Admixture	Rheomac VMA 358 and Acti-Gel® 208, Gypsum from EM Science

2.2.2. Paste Mix Design Study

The rheology properties of various cement pastes were studied using a Brookfield R/S SST 2000 soft/solid rheometer. The purpose of this study was to investigate how SCMs and chemical admixtures influence the flow properties of paste/concrete.

The rheology test procedure is shown in Figure 2.5. A paste sample was first placed into the rheometer, and the sample was then pre-sheared at a rate of $15s^{-1}$ for 60 seconds. After the pre-shearing, the rheometer was stopped for 60 seconds, and the sample was stirred gently with a small spatula. Then, the sample was subjected to a controlled rate hysteresis loop: the shear rate increased from 0 to $50s^{-1}$ within 60 seconds, and it then decreased to $0s^{-1}$ within the next 60 seconds.

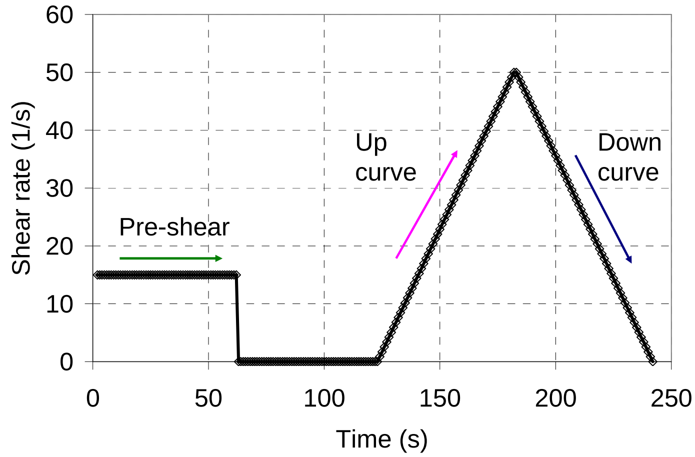


Figure 2.5. Shear rate for paste rheology test

A typical test result from the rheology test is shown in Figure 2.6. The yield stress and viscosity of the test sample were determined from the linear portion of the down curve. The yield stress was defined as the intersection of the linear portion of the down curve at the y-axis. The plastic viscosity was defined as the slope of the linear portion of the down curve.

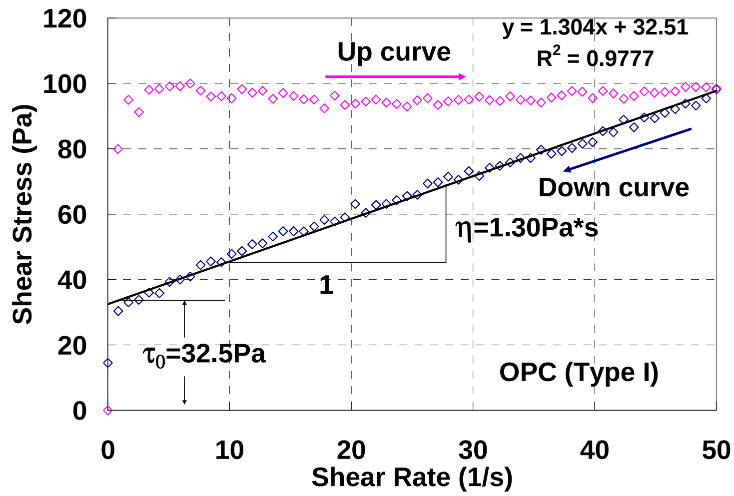


Figure 2.6. Typical test result for paste rheology test

Table 2.2 presents the mix proportions of the initial paste samples tested. These pastes had a water-to-binder ratio (w/b) of 0.40 and were mixed with a Hobart mixer according to ASTM C 305. The rheological test results are summarized in Figure 2.7.

Table 2.2. Mix proportions of the initial paste samples (w/b=0.4, Hobart mixer)

Paste	Description
OPC (Type I)	100% OPC
OPC+VMA	100% OPC with 6 fl oz Rheomac VMA 358 for 100 Ib cement
OPC-1.6Acti-gel	100% OPC with 1.6% Acti-gel by weight of cement
OPC-1.0Gypsum	100% OPC with 1% gypsum by weight of cement
90OPC+10 soil	90% OPC with 10% (Iowa loose) soil
70OPC+30FA-C	70% OPC with 30% Class C fly ash
70OPC+30FA-F	70% OPC with 30% Class F fly ash
70OPC+30LS Dust	70% OPC with 30% limestone dust
70OPC+30Slag	70% OPC with 30% GGBFS

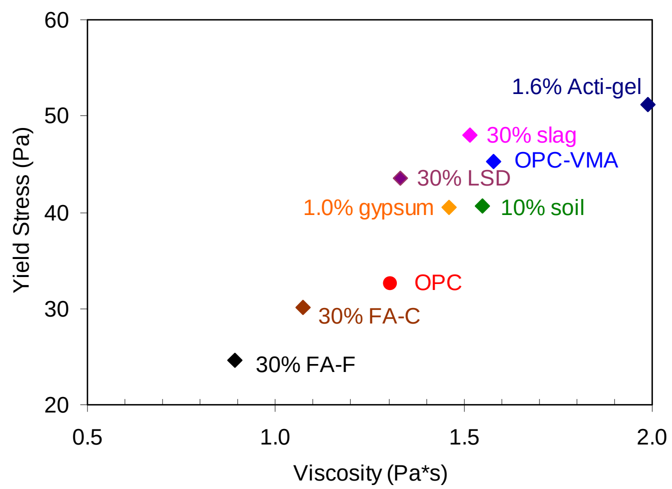


Figure 2.7. Rheology properties of the initial paste samples

The following observations were made based on the test results:

1. When compared with paste made with OPC, pastes made with both 30 % class C and F fly ash replacements had decreased both yield stress and viscosity.
2. Pastes made with 30% slag or 10% soil replacement had increased viscosity as well as increased yield stress, while pastes made with 30% limestone dust had an increased yield stress but no obvious change in viscosity.
3. Addition of the recommended dosage of Rheomac VMA 358 and Acti-Gel 208 increased both the yield stress and viscosity of the paste. The increases resulting from the addition of Acti-Gel 208 were more effective.

As discussed above, concrete having low yield stress and viscosity generally flows and compacts easily, but it may not be able to hold its shape well. Intermediate yield stress and viscosity values of pastes might be desirable for the SF SCC concrete mix design. In the following concrete mix design study, concrete compactibility was considered first, and then green strength, or shape-holding ability, was tested.

2.3 Concrete Mix Design Study

2.3.1 Gradation Evaluation

Six different coarse aggregate gradations, as shown in Table 2.3, were selected to study their effect on concrete compactibility and green strength, or shape-holding ability. Gradation G1 is currently used in the Iowa DOT C3 mix. G2 and G3 are the lower and upper gradation limits in ASTM C33, Standard Specification for Concrete Aggregate. G4 is the intermediate gradation of ASTM C33. G5 is an optimum aggregate gradation that meets the 0.45 power gradation curve standard. G6 is a trial gradation that was designed to limit the amount of large particles (19–25 mm) in G2. River sand with a fineness modulus of 2.87 was used as fine aggregate in the concrete.

Table 2.3. Aggregate gradation

Sieve Size (mm)	Coarse Aggregates % Passing						Sand % Passing
	G1	G2	G3	G4	G5	G6	
25.00	100.0	100.0	100.0	100.0	100.0	100.0	—
19.00	90.0	55.0	90.0	73.0	77.0	80.0	—
12.50	50.0	30.0	65.0	46.0	48.0	30.0	—
9.50	25.0	15.0	35.0	23.0	32.0	15.0	100.0
4.75	0.0	0.0	0.0	0.0	0.0	0.0	97.6
2.36	0.0	0.0	0.0	0.0	0.0	0.0	91.4
1.18	0.0	0.0	0.0	0.0	0.0	0.0	70.0
0.60	0.0	0.0	0.0	0.0	0.0	0.0	37.0
0.30	0.0	0.0	0.0	0.0	0.0	0.0	14.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	3.0
0.075	0.0	0.0	0.0	0.0	0.0	0.0	0.5

The loose and compact bulk density of coarse aggregates was first tested to evaluate the effect of aggregate gradation on concrete compactibility. Then, the compaction factor and slump cone tests for fresh concrete were performed to identify potential SF SCC mix proportions for further study.

Bulk Density of Coarse Aggregates: The loose and compact bulk density of the coarse aggregates were tested based on ASTM C 29/C 29M-97(2003), Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate. The results are presented in Table 2.4.

Table 2.4. Dry bulk density of graded coarse aggregates

No.	Bulk density (loose)		Bulk density (compacted		Difference
	(kg/m^3)	(lb/cf)	(kg/m^3)	(lb/cf)	(%)
G1	1348.7	83.6	1433.8	88.9	5.9
G2	1339.3	83.0	1470.4	91.2	8.9
G3	1332.8	82.6	1482.8	91.9	10.1
G4	1354.7	84.0	1513.4	93.8	10.5
G5	1371.8	85.1	1499.2	93.0	8.5
G6	1384.9	85.7	1434.3	88.93	3.4

The difference between the loose and compacted bulk density of coarse aggregates is an indicator of the energy needed to make the coarse aggregate particles well-packed. The smaller the difference, the easier the aggregate will be compacted to its maximum density. According to the test results, aggregates G1 and G6 might give concrete better consolidation than aggregates G2 and G5, which might be better than aggregates G3 and G4. However, better consolidation does not necessarily indicate that the concrete will have better shape-holding ability.

Compaction Factor Tests: To verify the findings obtained from the bulk density test, a modified compaction factor test method was used to evaluate the compactibility of fresh concrete made with all selected aggregate gradations (Figure 2.8). A given mix design, shown in Table 2.5, was used in the compaction factor tests. Previous research showed that when the sand-to-total aggregate ratio was about 45%, the minimum total energy was needed to compact fresh concrete (Liang et al. 2003). The mix design in Table 2.5 had a sand-to-total aggregate ratio of 44%.

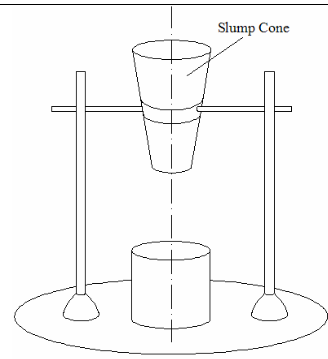


Figure 2.8. Compactibility tester

Table 2.5. Mix proportion of concrete made with different coarse aggregate gradations

	Trial Mix kg/m^3 (lb/yd^3)
Cement	481 (810)
Water	184 (311)
Sand	753 (1269)
Limestone	961 (1620)

In the concrete compactibility test, fresh concrete was poured from a constant height into a container through the slump cone. The container was specified by ASTM C138-01 for concrete unit weight test. After striking off the excess concrete and smoothing the surface, the weight of the concrete sample was measured and the uncompacted density of the fresh concrete was calculated. In the meantime, the compacted density of the same fresh concrete was also obtained according to ASTM C138-01. The ratio of uncompacted-to-compacted density values is defined as the compaction factor. The larger the compaction factor, the better compactibility the fresh concrete will have.

The compaction factor test results are presented in Table 2.6. Figure 2.9 illustrates the relationship between the compaction factor of fresh concrete and the compatibility of coarse aggregate, in terms of the difference between loss and compacted aggregate density.

Table 2.6. Compaction factor of concrete made with different coarse aggregate gradation

	Compaction Factor
G1	0.904
G2	0.916
G3	0.886
G4	0.859
G5	0.908
G6	0.939

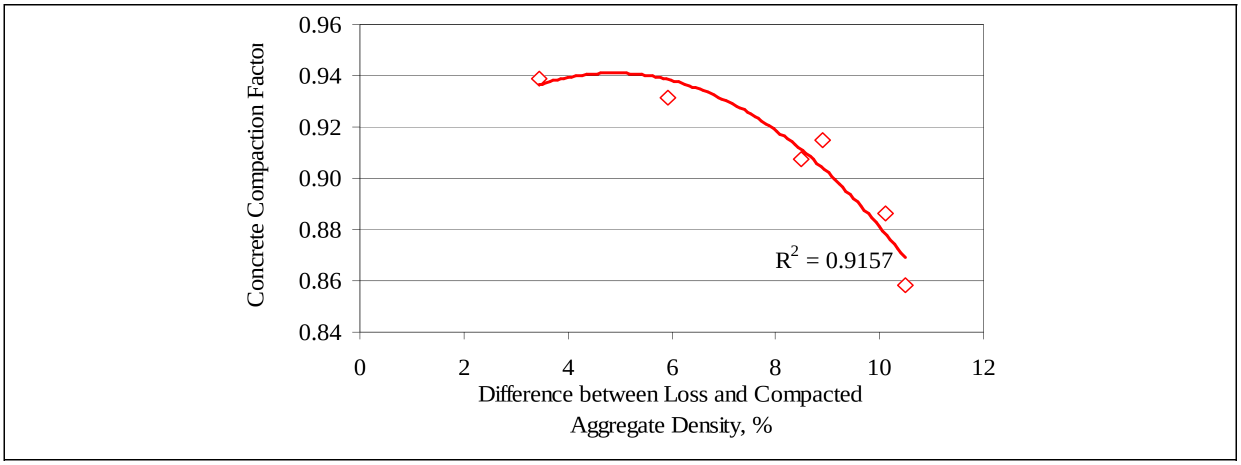


Figure 2.9. Relationship between aggregate and fresh concrete compactibity

Table 2.6 and Figure 2.9 indicate consistent results from the aggregate bulk density tests. That is, aggregate G6, having the smallest difference in loss and compacted aggregate density, resulted in the best concrete compactibility (the highest compaction factor). Based on this relationship, the fresh concrete compactibility can be assessed from loss and compacted aggregate density test results. As a result, the G6 graded aggregate was chosen for further study on the compactibility and shape stability of fresh concrete.

2.3.2. Concrete Mix Proportion Evaluation

Slump Cone Tests: Modified slump cone tests were used to evaluate concrete flowability and compactibility further, as well as to assess concrete shape-holding ability. The modified slump cone test is similar to the standard slump cone test (ASTM C143), except no rodding or vibration is applied during sample preparation. The concrete mix proportions in Table 2.7 were selected for the slump cone tests.

Table 2.7. Concrete mix proportion, kg/m^3 (lb/ft^3)

Mix	Cement	Fly ash	Water	Sand	Limestone (G6)
REF-0.35	485 (30)	0 (0)	170 (10.5)	753 (47)	961 (60)
40C-0.35	291 (18)	194 (12)	170 (10.5)	753 (47)	961 (60)
30F-0.35	340 (21)	146 (9)	170 (10.5)	753 (47)	961 (60)
50F-0.35	243 (15)	243 (15)	170 (10.5)	753 (47)	961 (60)
30C-0.40	328 (20.5)	140 (8.7)	187 (11.7)	753 (47)	961 (60)
30F-0.40	328 (20.5)	140 (8.7)	187 (11.7)	753 (47)	961 (60)
25C-0.40*	351 (22)	117 (7.3)	187 (11.7)	753 (47)	961 (60)
30C-0.40*	328 (20.5)	140 (8.7)	187 (11.7)	753 (47)	961 (60)
40C-0.40*	280 (17.5)	187 (11.7)	187 (11.7)	753 (47)	961 (60)

*This group of samples was prepared in a different time period (November 2004) from others (May 2005).

Figure 2.10 presents the slump and spread values of the concrete mixtures, and Figure 2.11 illustrates the shape of the concrete mixture after the slump cone was removed. It was observed that mixtures having a w/b of 0.40 with 25% or 30% Class C fly ash (25C-0.40*, 30C-0.40, 30C-0.40*) not only had a desirable slump, but also a regular shape after the slump cone was removed. Based on the information discussed in section 2.1, these mixtures may not only have good flowability (or self-compactibility), but also good shape-holding ability. As illustrated in Figure 10, the slump and spread values of the concrete mixtures were approximately 8 in. (200 mm) and 14 in. (350 mm), respectively. These values, circled in Figure 10, were between the conventional slip-form paving concrete (C3) and conventional SCC, much closer to those of conventional SCC.

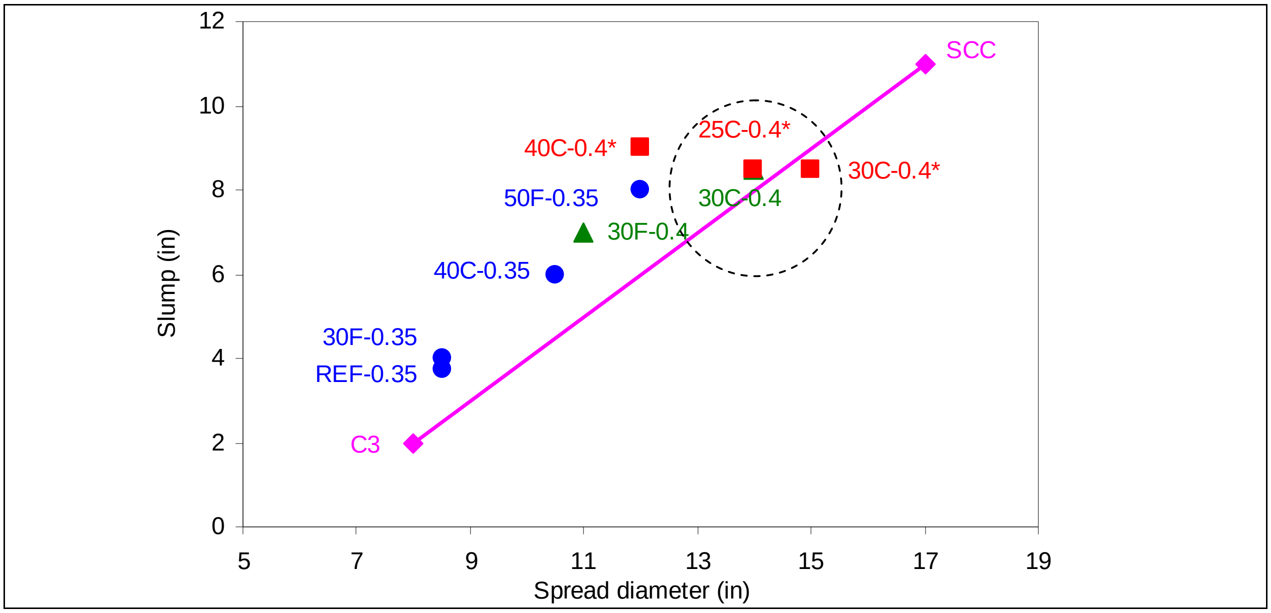


Figure 2.10. Relationship between concrete slump and spread

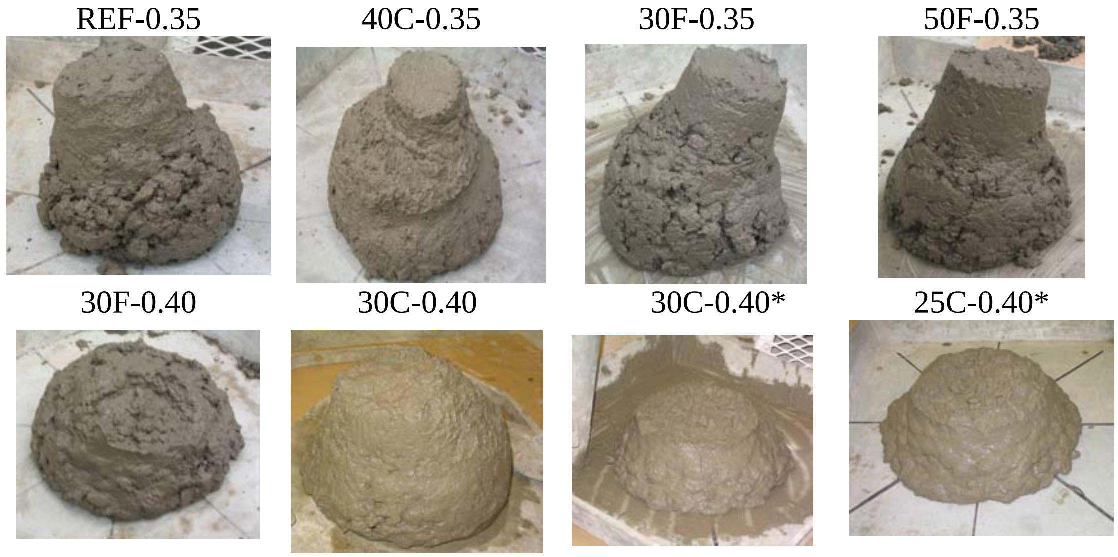


Figure 2.11. Shape of concrete mixture after slump cone test

2.4. Concrete Green Strength Test Development and Test Results

After identifying the potential SF SCC mixtures, the ISU researchers then developed a simple test method for evaluating the green strength of the concrete mixtures. The test procedure and some test results are presented below.

2.4.1. Test Procedure for Concrete Green Strength Measurement

In this simple test, a plastic cylinder mold (4 in. x 4 in. or 10 cm x 10 cm, without bottom) was used for concrete casting. During the casting, the SF SCC mixture was poured into the cylinder molds at a given height (12 in.) with no additional consolidation applied. Immediately after the cast, the plastic mold was removed and the shape of the concrete sample was examined. If a mixture demonstrated little or no deformation after the mold was removed, the mixture was considered to have good shape-holding ability, and the green strength test of the sample was then pursued. A large plastic cylinder (6 in. x 12 in. or 15 cm x 30 cm) was placed on the top of the fresh concrete sample. A small amount of sand was then slowly but continuously poured into the large plastic cylinder until the sample collapsed. The total amount of sand applied during the test divided by the loading area of the sample defined the green strength of the concrete. Figure 2.12 illustrates the test procedure for concrete green strength measurement.

	
(a) Test setup: slump cone placed on top of a plastic mold without the bottom	(b) Casting: mold is filled with fresh concrete without rodding or vibration
	
(c) Demolding: after plastic mold is removed, some concrete holds its shape	(d) Loading: big cylinder is placed on top of fresh concrete sample; sand is then gradually loaded into cylinder until sample fails

Figure 2.12. Test procedure for concrete green strength measurement

2.4.2. Effect of Acti-gel on Concrete Green Strength

As shown in Table 2.8, researchers found that the green strength of the potential SF SCC developed at ISU (cast with no additional consolidation) was only one-third of the green strength of conventional pavement concrete (C3 mixture, cast with rodding). Although having a low green strength, the potential SF SCC did self-consolidate and held its shape very well immediately after casting and removal of the mold. Addition of Acti-gel into the SF SCC mixture could significantly increase the concrete green strength.

Table 2.8. Effect of Acti-gel on concrete green strength

Mix	Strength at a given deformation, psi		Strength at failure, psi
	@ 3.2 mm (1/8”)	@ 19 mm (3/4”)	
C3 (rodded)	0.66	1.33	1.33
SF SCC (no rodding) (30% C-fly ash, w/b=0.42)	0.35	—	0.35
SF SCC with Acti-gel (0.5% of binder, no rodding) (30% C-fly ash, w/b=0.44)	0.50	—	0.50

2.4.3. Relationship among Concrete Compactibility, Green Strength, and Shape-Holding Ability

A set of concrete green strength tests was conducted to find the relationship among concrete compactibility, green strength, and shape-holding ability. As shown in Figure 2.13, for concrete mixtures placed with a given potential energy (without any rodding or vibration), the concrete green strength decreased as concrete compactibility increased. Although some concrete mixtures (the mixtures with a compactor factor of 1.00) had low green strengths, they could still hold the concrete shape well. Based on the observations from slump cone and green strength test results, it appeared that the concrete mixtures that had compaction factors larger than 0.99 could hold their shape well. Further research is necessary to verify the relationship among concrete compactibility, green strength, and shape-holding ability.

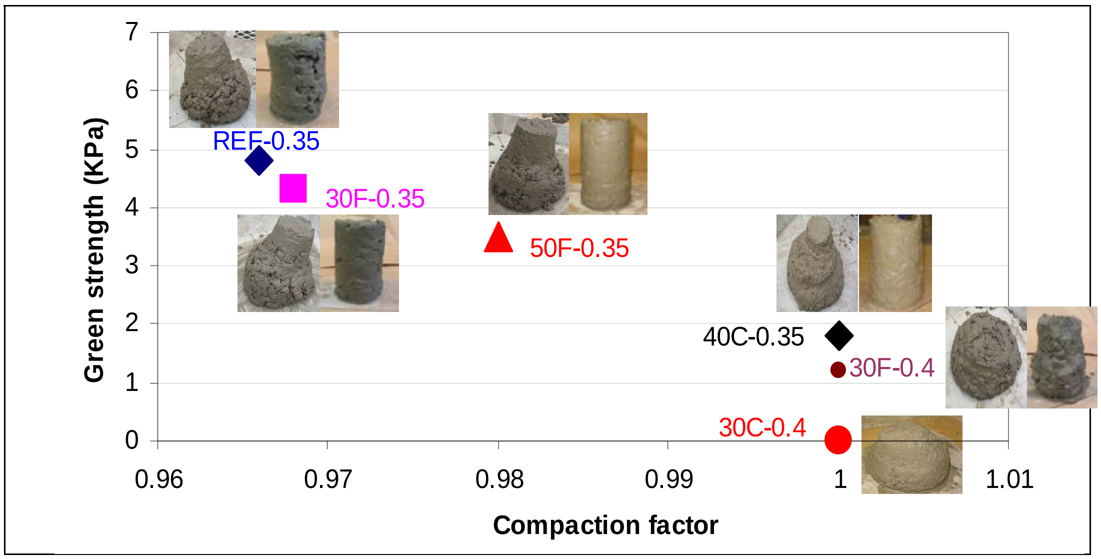


Figure 2.13. Relationship among concrete compactibility, green strength, and shape-holding ability

2.4.4. Effect of Pressure on Concrete Shape-Holding Ability

In the present study, a few tests were conducted to evaluate SF SCC flow ability using the L-box, which is commonly used to measure conventional SCC flow ability. As shown in Figure 2.14, the research indicated that for a given concrete mixture, a proper pressure needed to be applied to make the concrete flow without loss of shape-holding ability. When the vertical tube of the L-box had a 38-cm or 15-in. pressure, a SF SCC mixture kept a good shape after flowing out of the box. When the pressure was doubled, the SF SCC mixture flowed out the box rapidly and lost its shape-holding ability. The effect of the amount of pressure on SF SCC shape-holding ability may be important for successful application of SF SCC in field paving, and it will be studied further in the second phase of this project.

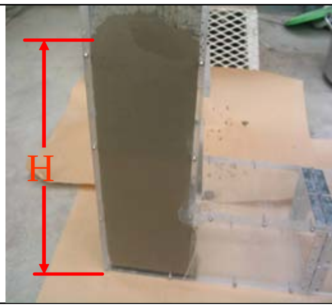
	H= 38 cm or 15”	H= 76 cm or 30”
		

Figure 2.14. Effect of pressure on concrete shape-holding ability

2.5. Simulation of the Field Paving Process in Lab to Prove the Potential Mix Design

2.5.1. Mini-paver Equipment and Test Method

In order to find out whether the newly developed SF SCC was applicable to field paving, the ISU research team developed a simple mini-paver for paving SF SCC segments in the lab. Considering that SF SCC may need a certain pressure to consolidate, the mini-paver was designed based on an L-box concept. As shown in Figure 2.15, the mini-paver system consists of (1) an L-box with a platform on top, (2) a towing system (a towing cable and a crank), and (3) a working table. The L-box had was 18 in. wide, 24 in. long, 18 in. high, and 3 to 6 in. thick. It could pave a concrete pavement section 18 in. wide x 3 to 6 in. thick x 48 in. long in the lab using two cubic feet of concrete mixture.

	
(a) front view	(b) back view

Figure 2.15. Mini-paver

Immediately before paving, concrete was stored on the platform and approximately 200 ponds of weights were placed on the paver (in a chamber). A stop plate was positioned at the end of the horizontal leg of the L-box. To begin paving, concrete is pushed from the platform into the vertical leg of the L-box up to a certain height; this action generates pressure to consolidate the concrete. Then, the stop plate is removed and the crank system is turned at a designed speed (3–5 ft/min), which will pull the mini-paver forward. As the mini-paver moves forward, it extrudes the concrete, or a pavement slab, out of the horizontal leg of the L-box.

2.5.2. Mini-paver Test Results

Potential SF SCC mixes were selected and tested with the mini-paver developed at ISU. The thickness of the mini-paver pavement section was set at four inches.

As shown in Figure 2.16, the mini-paver test demonstrated that well-designed SF SCC mixtures could not only self-consolidate, but also hold their shape very well after coming from the paver. The top surface of the final pavement section was smooth, and little or no edge slump was observed. The success of the mini-paver tests has provided the research team members with great confidence about the potential success of the new concrete technology, SF SCC, in the field.

Figure 2.16. Mini-paver test section for SF SCC

After the concrete was hardened, the mini-paver test section was cut into smaller sections. Three 50-mm (2 in.) and 100-mm (4 in.) diameter cores were taken at the age of 9 days for compressive and split tensile strength tests, respectively. The average concrete compression strength was 4,900 psi, and the average split tensile strength was 420 psi. A cross-section of the SF-SCC section showed no visible honeycomb and segregation, and the aggregate distribution was as good as that of conventional pavement concrete (Figure 2.17).

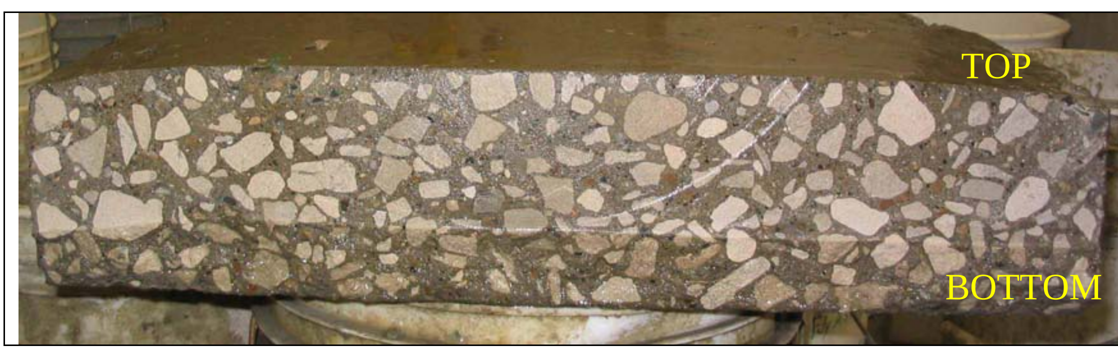


Figure 2.17. Cross-section of pavement slab

The filling ability of SF SCC in a pavement with dowel bars was also simulated and evaluated using a 30-cm (12-in.) cubic wooden box shown in Figure 2.18 (a). The diameter of the simulated dowel bar (a plastic piper) was 60 mm (1.5 in.), and the net distance between the dowel bar and box was 13 cm (5.25 in.). Concrete was poured into the box from the top, and the concrete then filled up the whole box without any tamping or vibration.

(a) dowel bar position	(b) dowel-concrete interface

Figure 2.18. Dowel bar test box and concrete slice

After demolding, the concrete sample was cut along and across the dowel bar, and the interface between the concrete and dowel bar was examined. As shown in Figure 2.18 (b), no visible air pockets were found at the dowel-concrete interface. Later, a mini-paver test was performed with two simulated dowel bars (perpendicular to each other) in a 100-mm (4 in.) thick paving section. Again, the SF SCC showed good filling ability around the dowel bars.

2.6. Preliminary Study of Engineering Properties of SF SCC

Concrete quality control tests, such as slump, set time, heat of cement hydration or maturity, and 1-day, 3-day, 7-day, and 28-day compressive strength were performed for the same SF SCC mix that was used for the mini-paver test. These test results are presented in the following sections.

2.6.1. Set Time Result

The set time test was performed according to ASTM C 403, Test Method for Time of Setting of Concrete Mixture Paste by Penetration Resistance. The results are shown in Figure 2.19 and compared with that of a Texas DOT pavement concrete mix. The initial setting times of these two mixes were very close, but the final setting time of SF SCC was earlier.

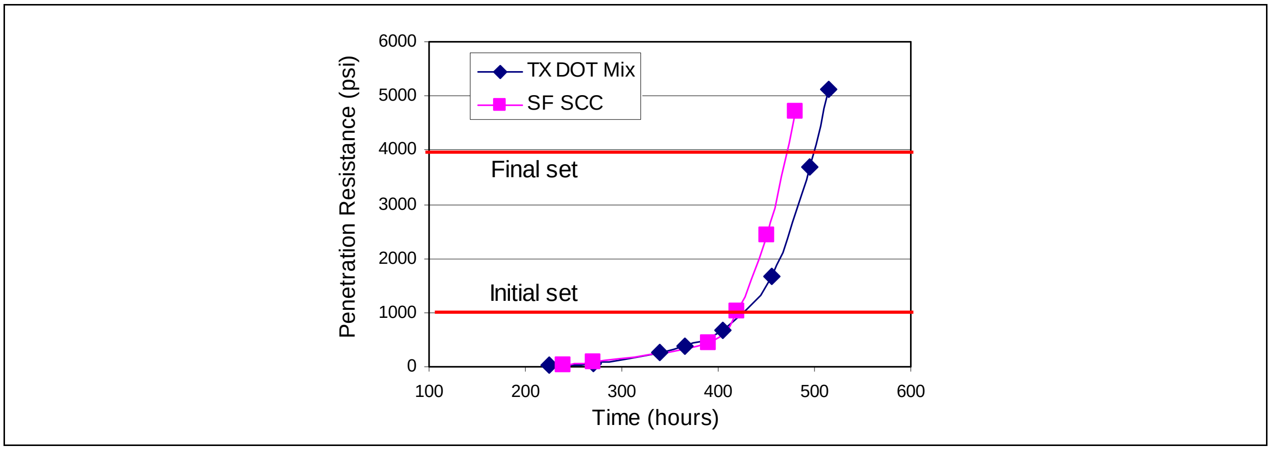


Figure 2.19. Setting time of a potential SF SCC mixture

2.6.2. Heat of Cement Hydration or Maturity

A heat of cement hydration test was conducted using an adiabatic calorimeter (IQdrum). The results for the SF SCC mix chosen for the mini-paver test are shown in Figure 2.20.

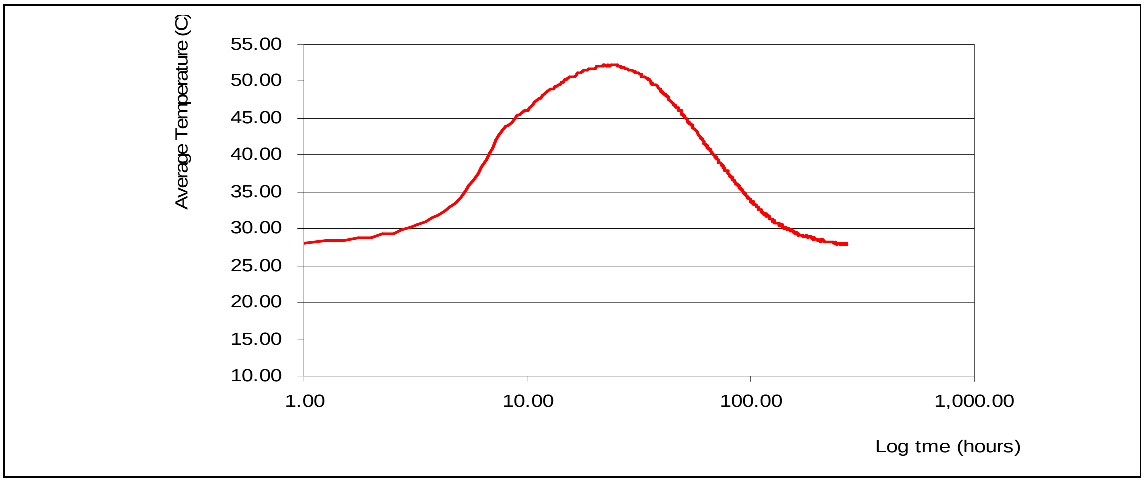


Figure 2.20. Heat of hydration of a potential SF SCC sample

2.6.3. Compressive Strength

Compressive strength tests were conducted for SF SCC at the age of 1, 3, 7, and 28 days; the results are shown in Figure 2.21. The strength development of SF SCC is comparable to that of Iowa DOT mix C3.

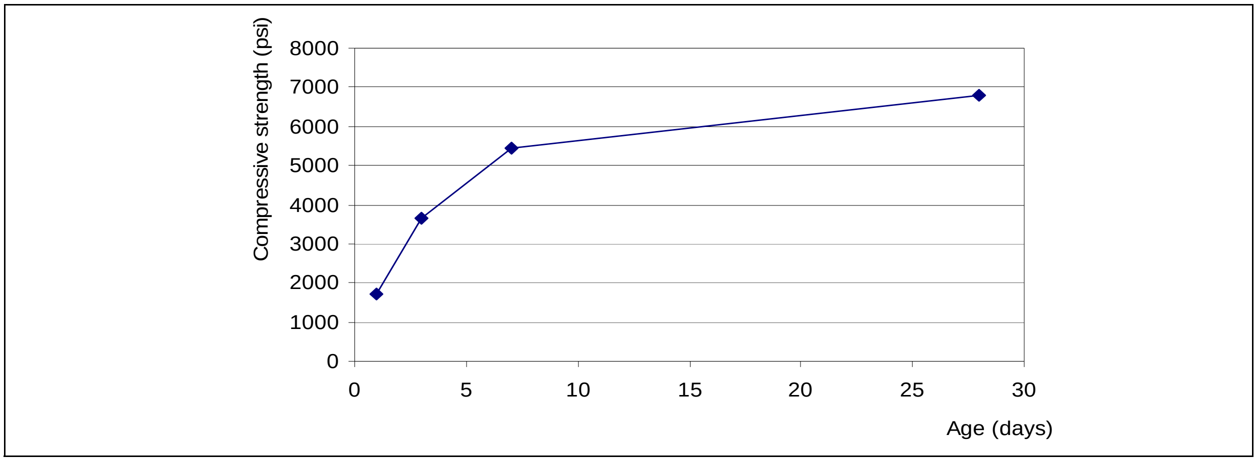


Figure 2.21. Strength development of SF SCC

2.7. Conclusion

This study demonstrated that a rational balance between flowability and shape stability can be obtained through concrete mix design. Development of a new type of concrete for slip form paving without vibration, SF SCC, is possible. More research is needed to refine the SF SCC mix design, study the effects of time and pressure on SF SCC shape-holding ability, investigate the general engineering properties and durability of SF SCC, and explore possible field paving equipment modifications before the SF SCC mix design is actually used in field paving.

3. NORTHWESTERN UNIVERSITY WORK

3.1. Introduction

This project is aimed at developing a concrete composition that increases the compactibility of the fresh material without sacrificing its shape retention. The concrete currently used for the slip-form paving process needs internal and external vibration to achieve satisfactory compaction. The internal vibration, which is introduced by vibrator fingers, often results in vibrator trails on the surface of the pavement and areas of lower air-entrainment due to over vibration. Additionally, segregation is often observed around the vibrator line. To overcome these problems, low compaction energy concrete will be developed in order to eliminate the need for internal vibration. This concrete may not be as fluid as self compacting concrete, but it should be workable enough for machine placement, be compactable with a minimum of energy, and hold its shape and have sufficient green strength after the slip-form paving process. This project is conducted in collaboration with the PCC Center at Iowa State University.

The conducted research focused on the systematic investigation of different factors that affect the flowability of fresh concrete mixtures. Specifically, the following parameters where examined:

- Type and content of plasticizer
- Paste content
- Type and content of clay
- Fly ash addition

The investigations were conducted by adapting the mixture proportion of a conventional self-consolidation concrete. It was then examined how the flowability of this concrete can be manipulated to combine the good flow properties with the shape stability required for concretes used for slip-form paving.

3.2. Factors Affecting the Flowability of a Model Concrete

3.2.1. Test Methods and Materials

The influence of different fine materials on the flowability of cement paste and concrete was evaluated by using the flow test, the drop table test, and by measuring the green strength of the fresh concrete mixtures. The flow test measures the flow diameter of a fresh cement paste or concrete after a brass cone, which was filled with the material, is lifted. No external force is applied in this test. The test is shown in Figure 3.1.

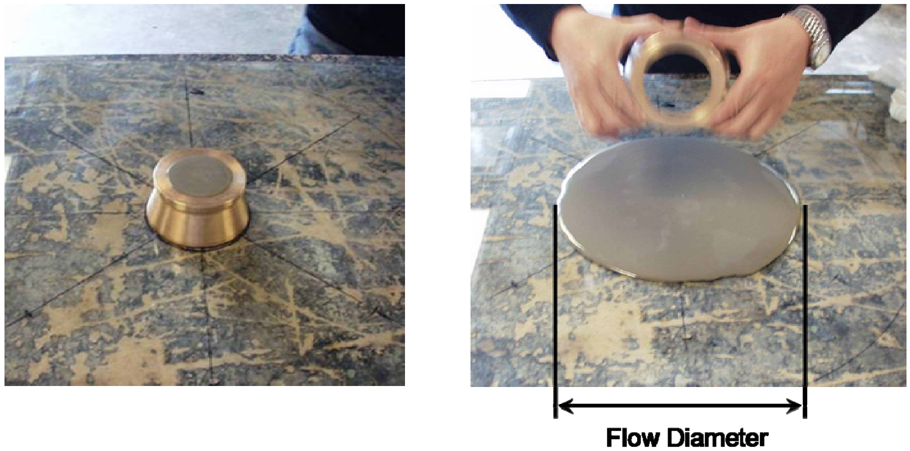


Figure 3.1. Determination of the flow diameter of fresh cement paste with the flow test

The drop table test measures the flow diameter of the test material after the table that supports the concrete or cement paste was subjected to 25 drops. This test can only be applied to materials which have the ability to maintain shape after the cone is lifted. The test setup is shown in Figure 3.2.

In addition to determining the flow diameter, the drop table was used to evaluate the shape stability of the tested materials after compaction. This was achieved by loosely filling a 4 x 8 inch cylinder with the concrete, placing this cylinder on the drop table and then applying 25 drops. The cylinder was turned over and demolded. After the shape stability of the demolded cylinder was evaluated, a vertical force was applied to the cylinder until the specimen collapsed. The maximum force was used to calculate the green strength of the tested cylinder.

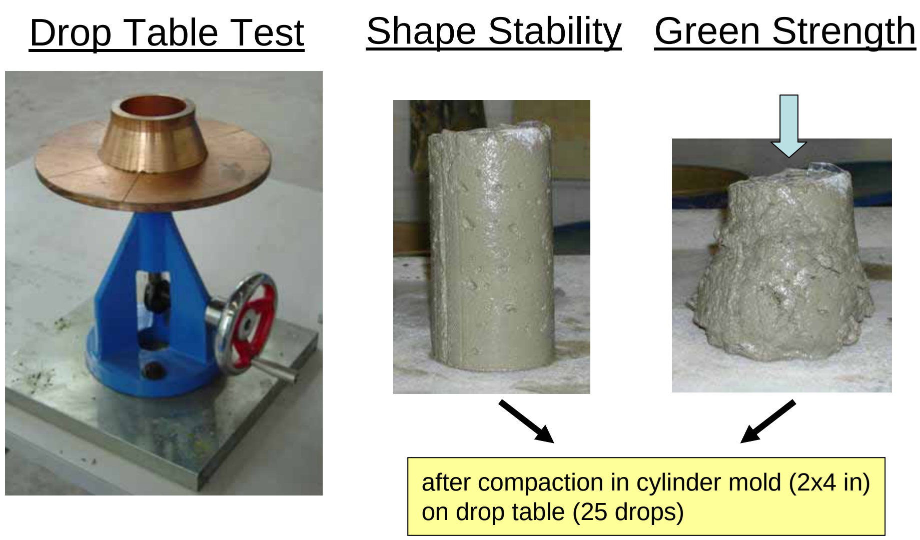


Figure 3.2. Test setup of the drop table test and a fresh concrete specimen before and after green strength test

The experiments were conducted with concretes whose mix design was adapted from a conventional SCC. All investigated concrete mixtures are compared to a plain concrete that represents a typical mix design that is used for slip-form paving by the Iowa Department of Transportation.

3.3.2. Influence of Type of Plasticizer

Experiments were conducted to investigate the influence of the type of plasticizer on the flowability and green strength of fresh concrete. The flow diameter of a conventional SCC mix design with a polycarboxylate-based plasticizer in different contents was compared with the same concrete mixture containing naphtaline-based plasticizer. Figure 3.3 shows that much less polycarboxylate-based plasticizer is needed to obtain a certain flow diameter.

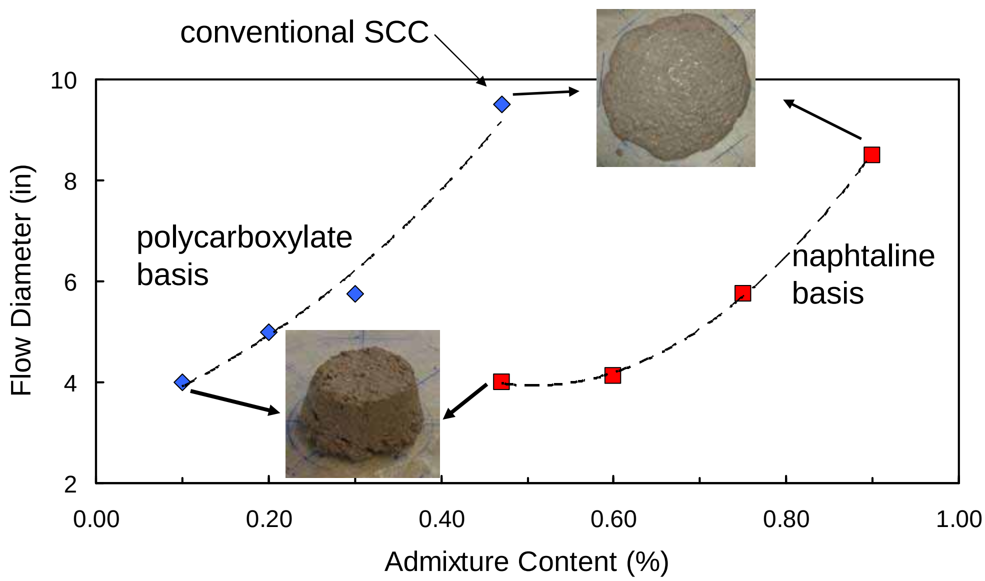


Figure 3.3. Relationship between flow diameter and plasticizer content for fresh concrete

The concrete mixtures that were found to have a flow diameter of 4 inch for the flow test (corresponding to a shape stable condition) were then tested with the drop table. The shape stable condition can be achieved with the plasticizer contents of 0.1% (polycarboxylate-based) and 0.47% (naphtaline-based). The development of the flow diameter of the two concretes determined with the drop table is given in Figure 3.4.

The concrete containing naphtaline-based plasticizer exhibits a higher flow diameter for any number of drops than the one containing polycarboxylate-based plasticizer. This indicates that naphtaline-based plasticizers have a positive effect on the flowability of concrete under the effect of external compaction energy. The plain concrete containing the naphtaline-based plasticizer in a content of 0.47% of cement weight will be taken as a reference mixture for comparison to all mixes that will be considered in the following sections.

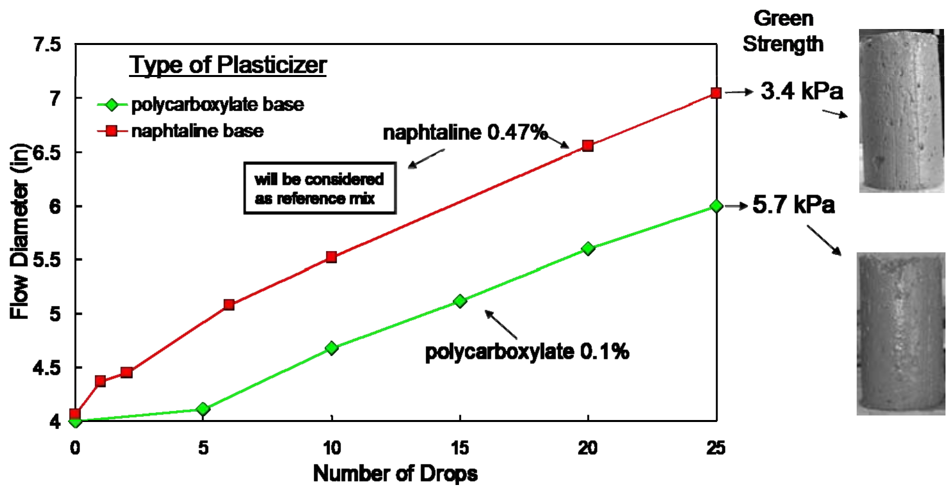


Figure 3.4. Effect of type of plasticizer on the flow diameter (drop table) and green strength of fresh concrete

3.2.3. Effect of Different Fine Materials on the Flowability of Concrete

The starting point of this investigation was a common SCC. This SCC was then modified by gradually adding different fine materials, such as fly ash, clay and cement itself, until the concrete reached a shape-stable condition after lifting the cone during the flow test. This condition refers to a flow diameter of 4 inch (dashed line in Figure 3.5). Figure 3.5 shows that the tested materials have a very different effectiveness in reducing the flowability of the concrete. The higher effectiveness of the clays is most likely due to the finer particle size compared to that of fly ash and cement powder.

Since clay seems to be very effective in manipulating the shape stability of concrete it will next be investigated how the clay addition influences the flow properties of concrete under the effect of external energy.

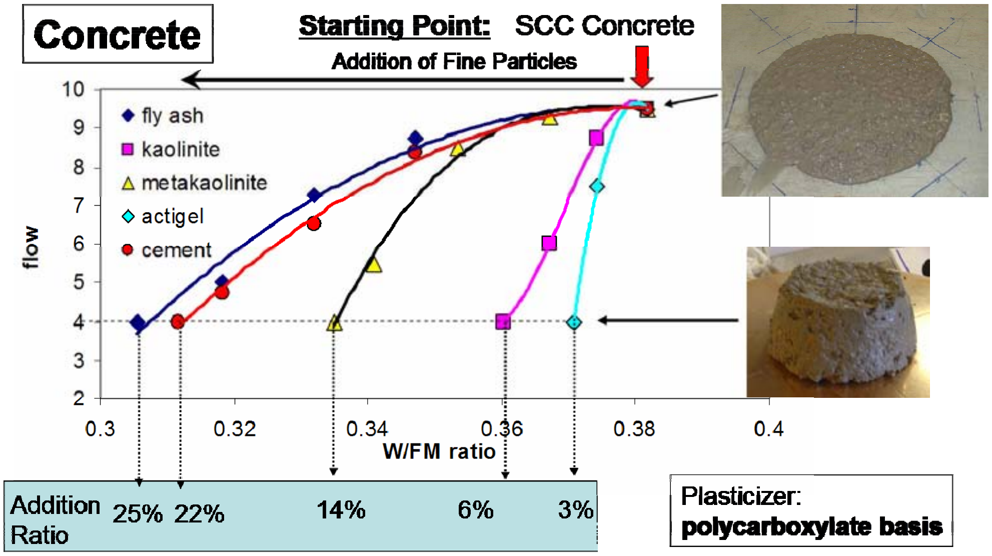


Figure 3.5. Effectiveness of different fine materials to reach a shape stable condition of cement paste

3.2.4. Effect of Acti-Gel on Flowability under External Energy

The effect of Acti-Gel on flowability and green strength under the effect of compaction external energy can be seen in Figure 3.6. The additive amounts of 1% and 2% (per cement weight) exhibit a better flowability when compared to the reference mixture. It should be noted that the 2% additive amount has the highest flow diameter, but exhibits a relatively low green strength. With respect to green strength it is more beneficial to choose an additive amount of 1%. This mix combines an improvement in shape stability and flowability compared to the reference concrete.

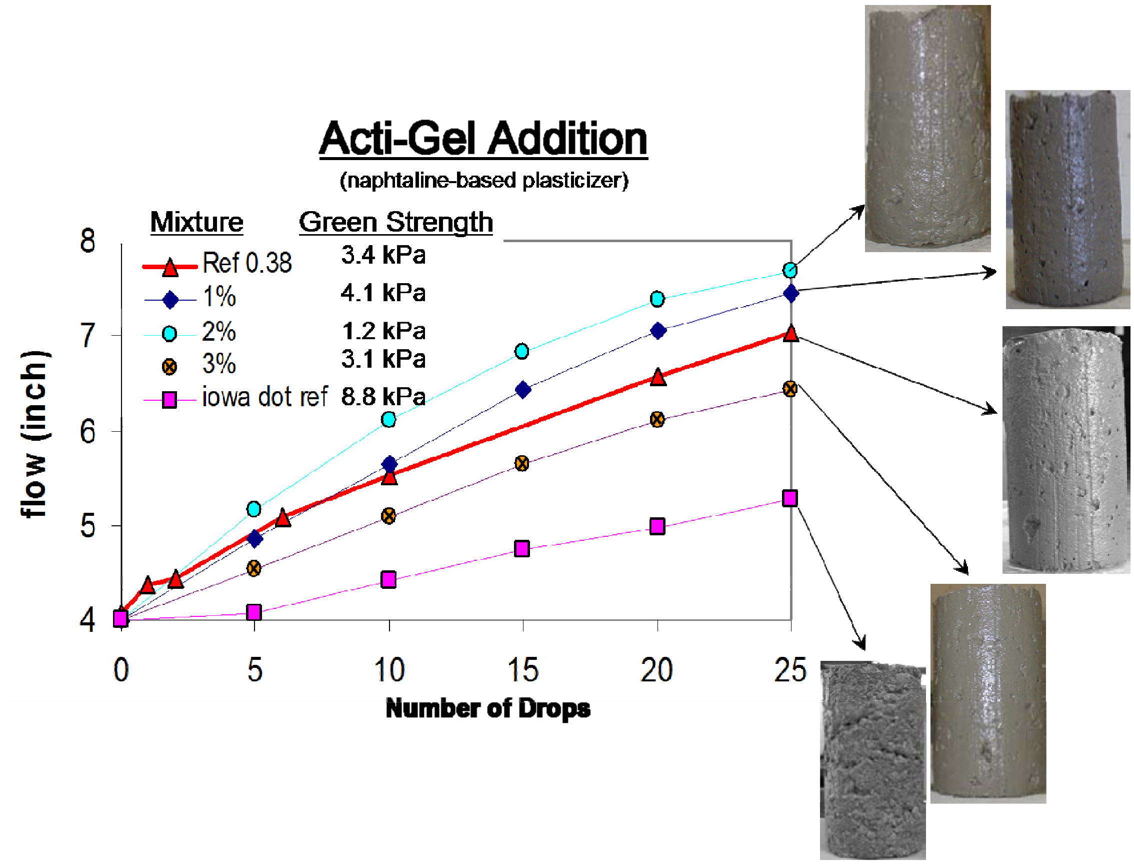


Figure 3.6. Effect of Acti-Gel on the flowability and green strength (additive amount in per cent of cement weight)

Table 3.1. Mixture proportions of tested concrete mixtures (kg/m^3)

	Acti-Gel mixes			Plain (Reference)
Addition Ratio Clay (per cement weight)	1%	2%	3%	—
Water	206.1	214.2	220.2	197.0
Gravel	854.0	845.4	829.6	859.0
Sand	787.4	779.4	764.9	792.0
Cement	513.0	507.8	498.3	516.0
Plasticizer (naphtaline)	2.4	2.4	2.3	2.4
Acti-Gel	5.1	10.0	15.0	—

3.2.5. Effect of Metakaolinite on Flowability under External Energy

The addition of metakaolinite clay is most beneficial when used in an additive amount of 1.5% of total concrete volume. When used in this rate the flow can be increased by maintaining the green strength compared to the reference mixture. The relationship between flow diameter and additive amount for all tested mixtures are given in Figure 3.7.

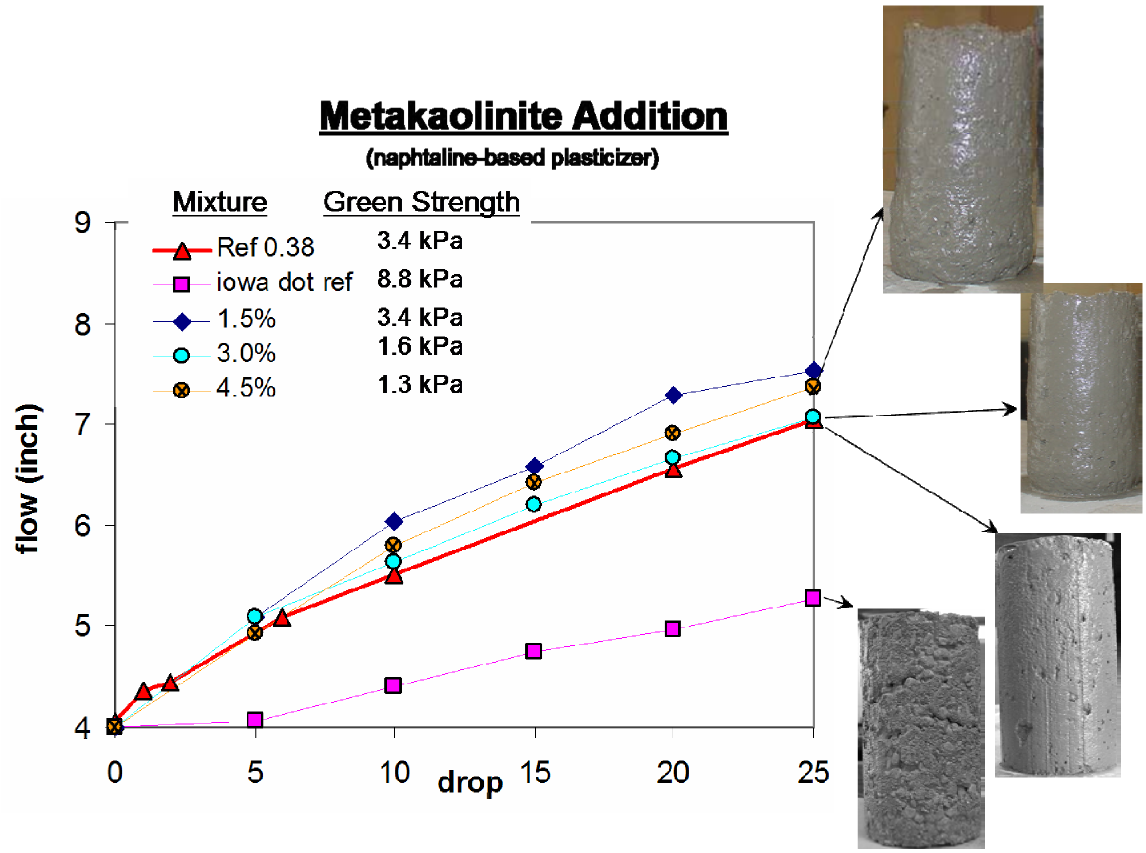


Figure 3.7. Effect of metakaolinite on the flowability and green strength (additive amount in per cent of cement weight)

Table 3.2. Mixture proportions of tested concrete mixtures (kg/m^3)

	Metakaolinite Mixtures			Plain (Reference)
Addition Ratio Clay (per cement weight)	1.5%	3.0%	4.5%	—
Water	200.2	205.1	207.9	197.0
Gravel	853.0	854.3	847.2	859.0
Sand	786.5	787.7	781.2	792.0
Cement	512.4	513.2	508.9	516.0
Plasticizer (naphtaline)	2.4	2.4	2.4	2.4
Metakaolinite	7.6	15.4	22.8	—

3.2.6. Effect of Kaolinite on Flowability under External Energy

The effect of Acti-Gel on flowability and green strength under the effect of compaction external energy can be seen in Figure 3.8. It is obvious that the flowability could not be improved significantly by any tested additive amount. However, the addition of kaolinite is very beneficial for improving the green strength of the material. The mixture with the additive amount of 1.5%

has a much higher green strength than the reference mixture, with only a small reduction of the flowability.

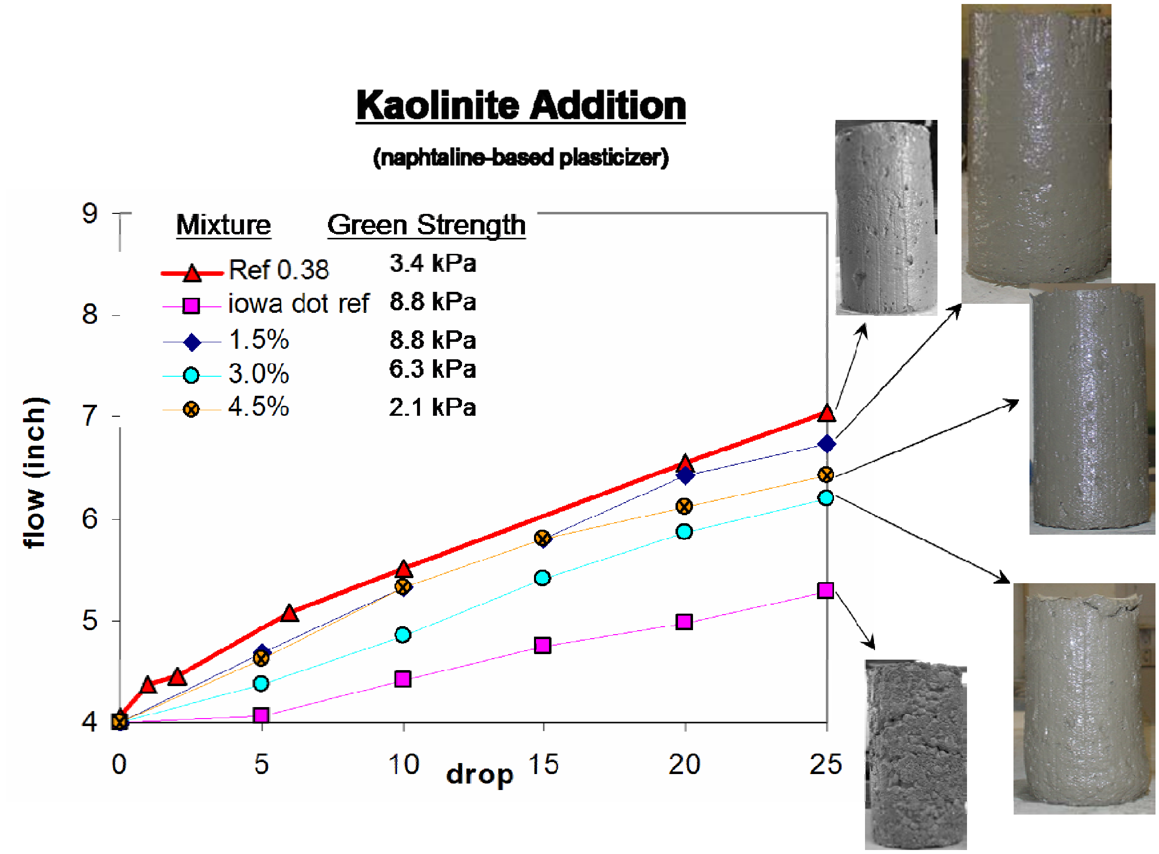


Figure 3.8. Effect of kaolinite on the flowability and green strength (additive amount in per cent of cement weight)

Table 3.3. Mixture proportions of tested concrete mixtures (kg/m^3)

	Kaolinite mixtures			Plain (reference)
Addition ratio clay (per cement weight)	1.5%	3.0%	4.5%	—
Water	204.6	205.7	207.9	197.0
Gravel	846.8	856.4	847.1	859.0
Sand	780.7	789.6	781.0	792.0
Cement	508.7	514.4	508.9	516.0
Plasticizer (naphtaline)	2.4	2.4	2.4	2.4
Kaolinite	7.6	15.4	22.8	—

3.2.7. Effect of Fly Ash on Flowability under External Energy

The effect of the partial replacement of cement with fly ash on flowability and green strength under the effect of compaction external energy is given in Figure 3.9. With respect to flowability, the replacement is most beneficial for the amount of 10% of original cement weight. This, however, has a detrimental effect on the green strength and the shape stability of the fresh concrete. No green strength could be measured. Nevertheless, it should be noted that the concrete does have certain shape retention. Future work will be done to improve the shape stability of this particular mixture. On alternative would be the addition of a small amount of clay. The other mixtures with replacement rates of 20% and 30% also exhibit a low green strength, but are located in the range of acceptable values. The flowability is close to that of the reference mixture.

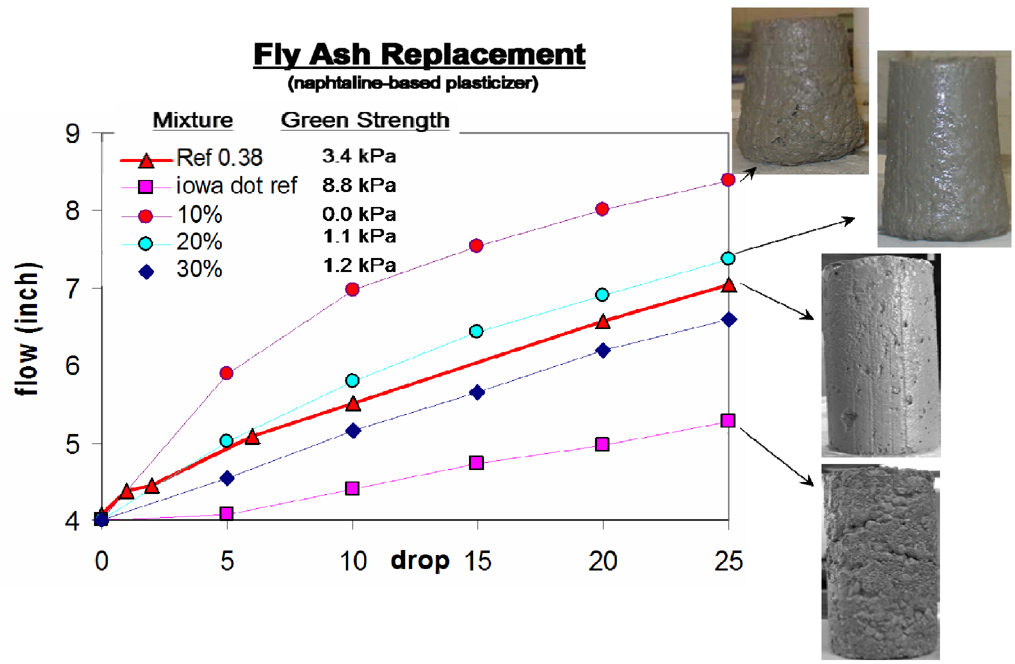


Figure 3.9. Effect of fly ash on the flowability and green strength (additive amount in per cent of cement weight)

Table 3.4. Mixture proportions of tested concrete mixtures (kg/m^3)

	Fly ash mixtures			Plain (reference)
Addition ratio fly ash (per cement weight of reference mix)	2%	2%	0	—
Replacement ratio fly ash (per cement weight)	31%	21%	10%	—
Water	194.5	195.1	196.8	197.0
Gravel	847.9	850.7	857.9	859.0
Sand	781.8	784.3	791.0	792.0
Cement	356.5	408.8	463.8	516.0
Plasticizer (naphtaline)	2.4	2.4	2.4	2.4
Fly ash	167.8	119.2	51.5	—

3.3. Relationship between Green Strength and Flowability

The relationship between green strength and flowability for all tested mixtures is given in Figure 3.10. It can be seen that the majority of the mixtures follow one main trend, which shows an increase of green strength with a decrease in flow diameter after 25 drops on the drop table. It can also be seen that certain mixtures are not part of this trend. These mixtures show a higher green strength (corresponding to a better shape stability) for a given flowability than other mixtures. These mixtures are potential candidates to be recommended for use in low compaction energy concrete.

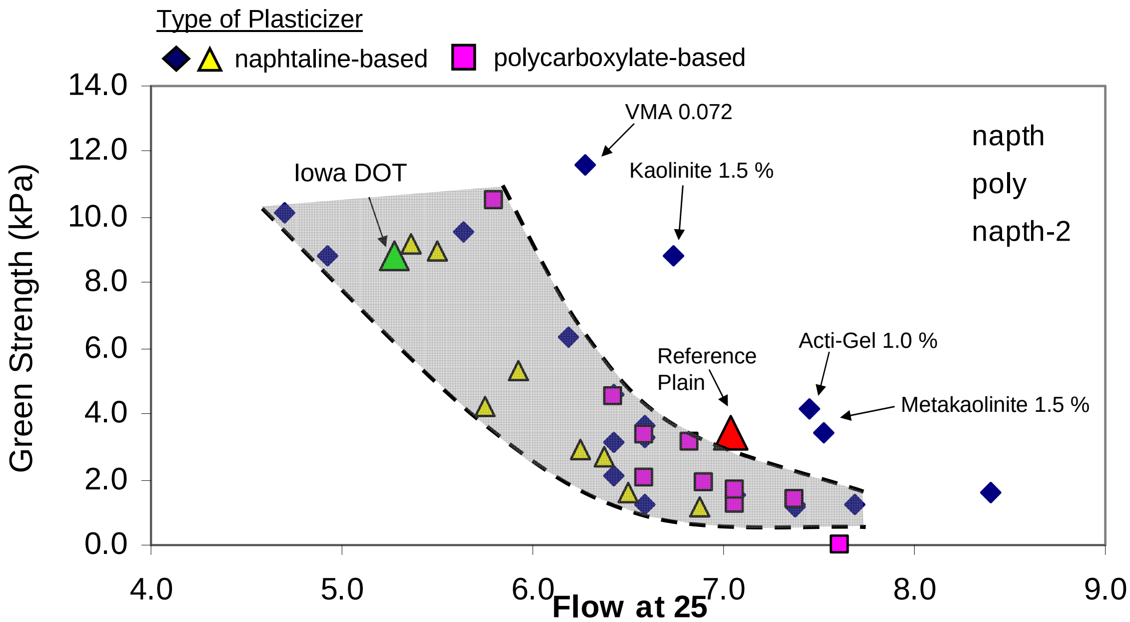


Figure 3.10. Relationship between green strength and flowability (flow diameter after 25 drops on drop table) for tested mixtures

3.4. Conclusion

In conclusion, in can be stated that it is necessary to have a high content of fine materials present in the fresh concrete to achieve a good balance between flowability and shape stability in fresh state. In this phase of the investigations, this was achieved by adopting and modifying the mix design of self-compaction concrete. Two main parameters were investigated: addition of fine particles and modification of the type of plasticizer. It was shown that both modifications lead to significant improvement of the flowability of the fresh concrete. For a given amount of external compaction energy (drops of drop table) a much better flowability compared to the Iowa DOT mix design could be achieved. Despite their relatively high flowability, these mixes have a very good shape stability in fresh state. In particular, the following mixtures have a good performance in both, green strength and flowability (all mixtures are based on a conventional SCC mix design):

- Mix 1: no addition, naphtaline-based plasticizer 4.7% of cement
- Mix 2: Mix 1 + 1% Acti-Gel (per cement weight)
- Mix 3: Mix 1 + 1.5% Metakaolinite (per cement weight)
- Mix 4: Mix 1 + 1.5% Kaolinite (per cement weight)

In addition to these mixtures, the concrete where 10% of the original cement was replaced with fly ash bears significant potential because of the large improvement of the flowability. It will be investigated how the shape stability can be improved to an acceptable value.

4. SPATIAL EVALUATION OF SELF-CONSOLIDATING CONCRETE COMPONENTS USING X-RAY COMPUTED TOMOGRAPHY SCANNING

4.1. Introduction

Self-consolidating concrete is developed to provide good workability without causing problematic settlement or requiring vibration for consolidation. Through the development process of new mixes it is important to monitor aggregate segregation and void distribution throughout a sample to ascertain that there is a homogenous distribution of all material phases. That need is met non-destructively by using X-ray computed tomography (X-ray CT).

X-ray CT offers the world of material engineering the unique ability to view internal characteristics of specimens nondestructively. This technology is made possible by using measurements of x-ray attenuation, which is a function of material density. In short, the product of this type of analysis is volumetric maps of material densities. The process works by positioning a sample inside an x-ray fan beam and casting its shadow upon a special camera or detector that translates x-ray energy into electrical current (see Figure 4.1). As the sample is rotated inside the X-ray fan beam, this shadow is translated into a two dimensional cross section. By measuring several of these cross-sections at small intervals, the cross sections can be stacked one upon another to form three dimensional digital representations of density within a sample. True microfocus X-ray CT, such as that used in this analysis, utilizes x-ray beam sources with spot sizes of only two to five microns and can produce volumetric digital files with effective pixel sizes of a few microns (Zhang et al. 2003).

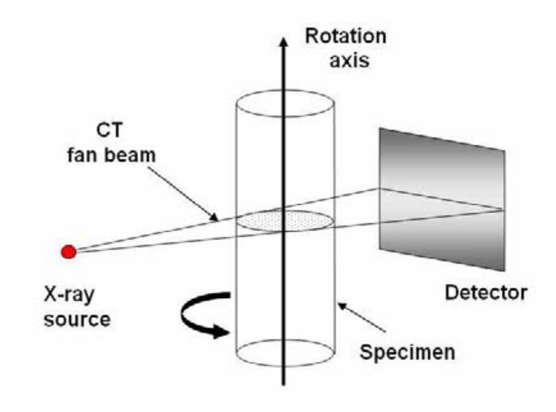


Figure 4.1. CT scanning setup

4.2. Objectives

The objectives of applying X-ray CT in the analysis of SCC are the following:

- Scan and digitally reconstruct 3-D images of concrete cylinders.
- View the three phases present in concrete (aggregate, cement, and air voids) and visually determine their homogeneity throughout each sample.

4.3. Dissecting a Sample: Methods and Materials

At Iowa State University's Center for Nondestructive Evaluation (CNDE) complete microfocus X-ray CT systems have been created including the development of customized software for data acquisition, volumetric file reconstruction and visualization. A 64 node Linux is used in the CT reconstruction. The chamber used for these scans utilizes a 130 kilovolt microfocus X-ray tube capable of 2.5 micron resolution and 1400 x 1400 x 500 voxel (3-D resolution unit) data volumes.

Three SCC samples of the same mix design were created by dropping concrete 12 inches into a 3 in. x 3 in. x 6 in. (7.6 cm x 7.6 cm x 15.2 cm) cylindrical mold and allowing cement to cure in order to simulate field placement (see Figure 4.2). In the design of SCC it is important to keep the densities of aggregate and cement similar so aggregate settlement does not occur (Wang 2003). Since objects with equivalent densities attenuate X-rays at an equivalent rate, mapping variations in densities can be challenging. Also, cement cylinders exhibit high densities (specific gravity of 2.3 +/-) and relatively thick diameters so samples attenuate X-rays easily, making imaging more difficult especially towards the center of cylinders where X-rays need to pass through the entire sample diameter. The effect is poorly defined edges between aggregate and cement, growing worse towards the sample's center (see Figure 4.3). It was found that by sending higher voltage and current through the X-ray tube the increase in electrical power increased the number and energy of X-rays passing through the sample improving the crispness of aggregate edges and allowing data from the center of the samples to be gathered (see Figure 4.4).

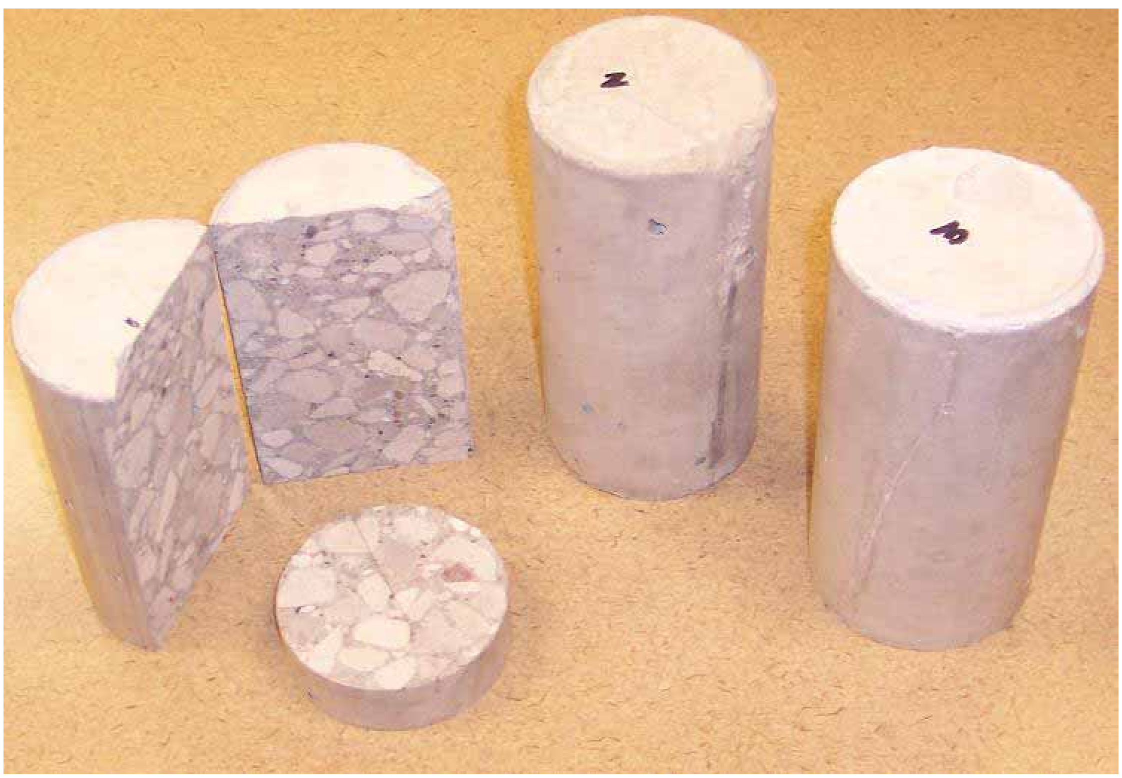


Figure 4.2. Self-consolidating concrete samples 1 (diamond saw cut), 2, and 3

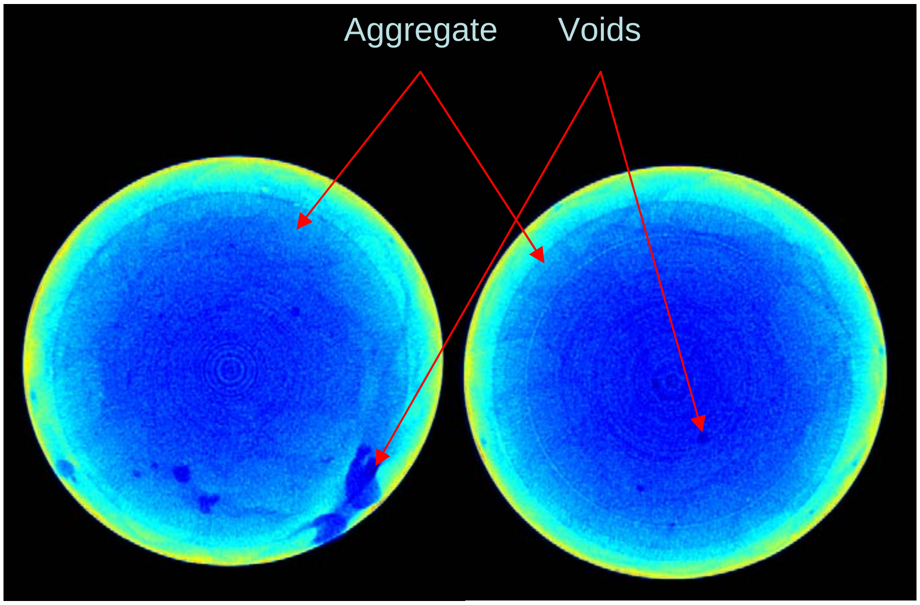


Figure 4.3. Two initial cross sections, blurred central regions

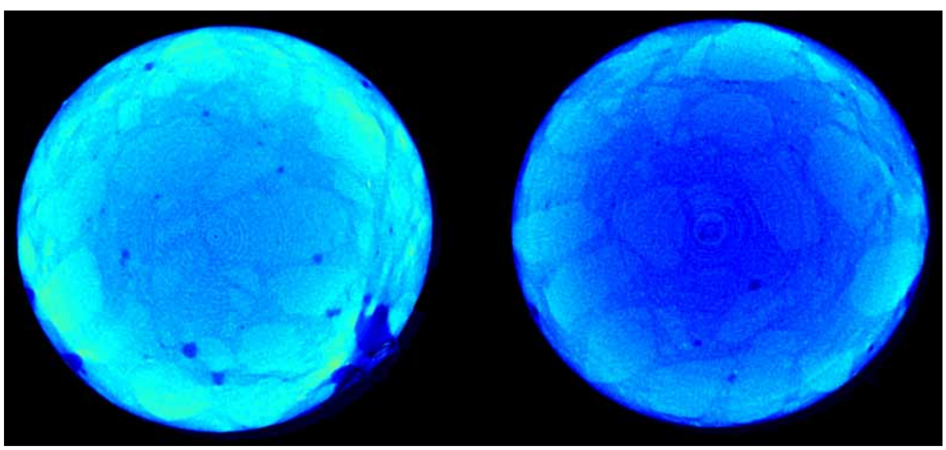


Figure 4.4. Scans using improved methods

The SCC samples illustrated in this paper were scanned to obtain three dimensional volumetric files of 640 x 640 x 310 voxels in size resulting in cross sectional resolution of 0.16 mm x 0.16 mm and vertical resolution of 0.49 mm. Scans were conducted at 130 kV and 0.45 mA. Also, a copper filter consisting of 0.005 inches of metal was placed over the end of the X-ray tube to attenuate low energy X-rays that absorb easily in the exterior of a sample's volume and result in erroneously high density values towards sample edges.

Each SCC sample is illustrated using the same series of sections within a sample. Six equally spaced slices are viewed perpendicularly to the central axis using three dimensional visualization software developed at CNDE (see Figure 4.5). Also, a series of profiles are viewed vertically through the cylinder. The first four profiles are slices taken towards the edge of the sample and touch each other their sides to portray a wrapping effect around the sample, referred to as wrapping edge profiles. Then a profile is taken directly across the samples center, referred to as the central profile (see Figure 4.6).

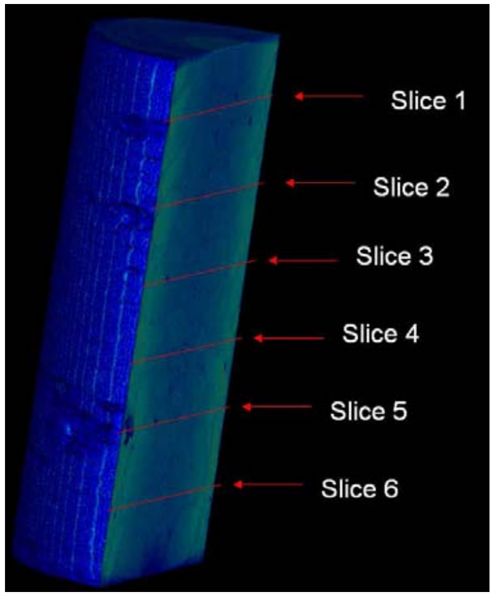


Figure 4.5. Depiction of the slices viewed within a sample

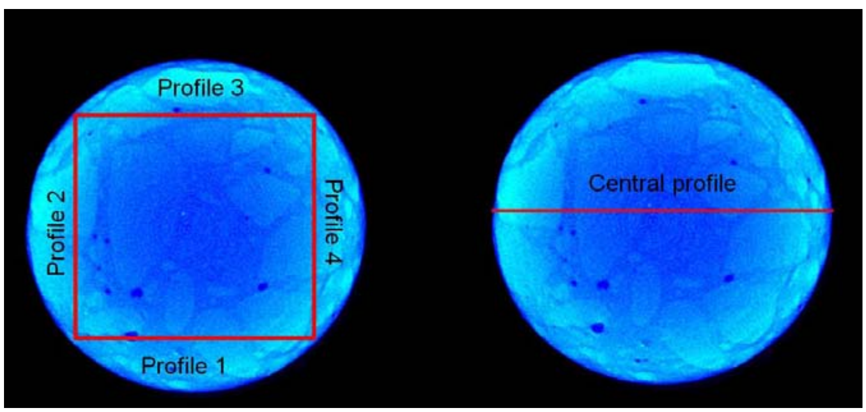


Figure 4.6. Depiction of the profiles viewed within a sample

4.4. Results and Discussion

Cross sectional slices and profiles of sample 1 (see Figures 4.7–4.9), sample 2 (see Figures 4.10–4.12), and sample 3 (see Figures 4.13–4.15) illustrate a random and seemingly homogenous distribution of aggregate and void phases within the concrete matrix except for near to top, towards the center of samples one and three where there is no large aggregate (see Figures 4.9 and 4.15). This effect is located too close to the sample center to be viewed in the wrapping edge profiles but becomes apparent in the central profile.

Two possible reasons for this lack of aggregate are (1) settlement prior to hardening or (2) segregation due to the 12-inch drop. If settlement is the cause, edge effects could be thwarting settlement towards the sample edge, causing only the central portion to be vacant of large aggregate. Obtaining core samples from a controlled field application without a drop height would show a uniform lack of aggregate at the top surface. If the 12-inch drop caused segregation then there would not be a lack of aggregate in the same experiment. Regardless, both possible causes are the result of a difference in density between aggregate and cement components.

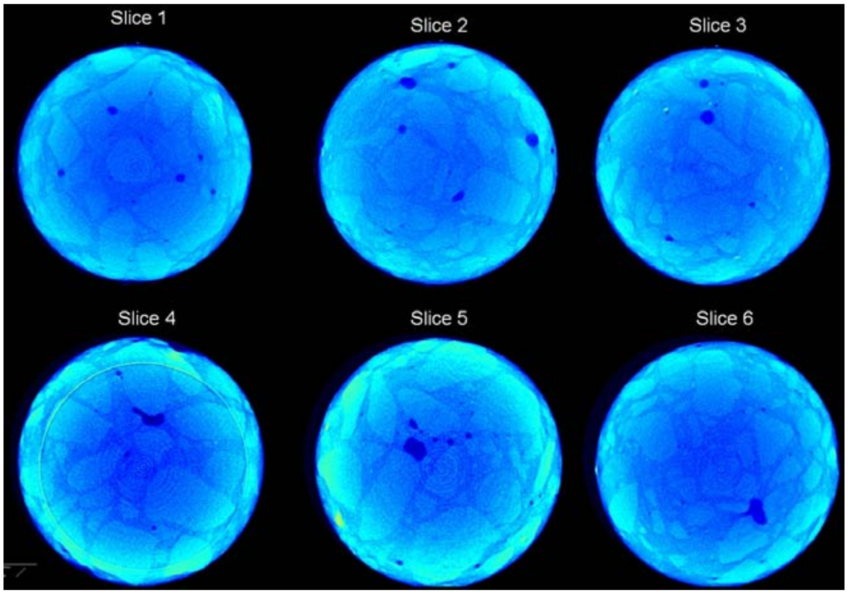


Figure 4.7. Sample one cross sectional slices

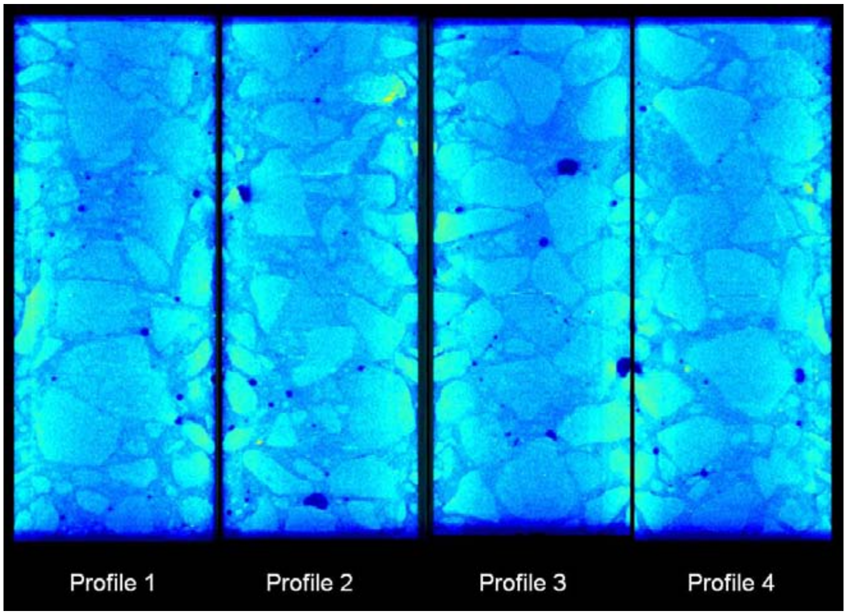


Figure 4.8. Sample one wrapping edge profiles

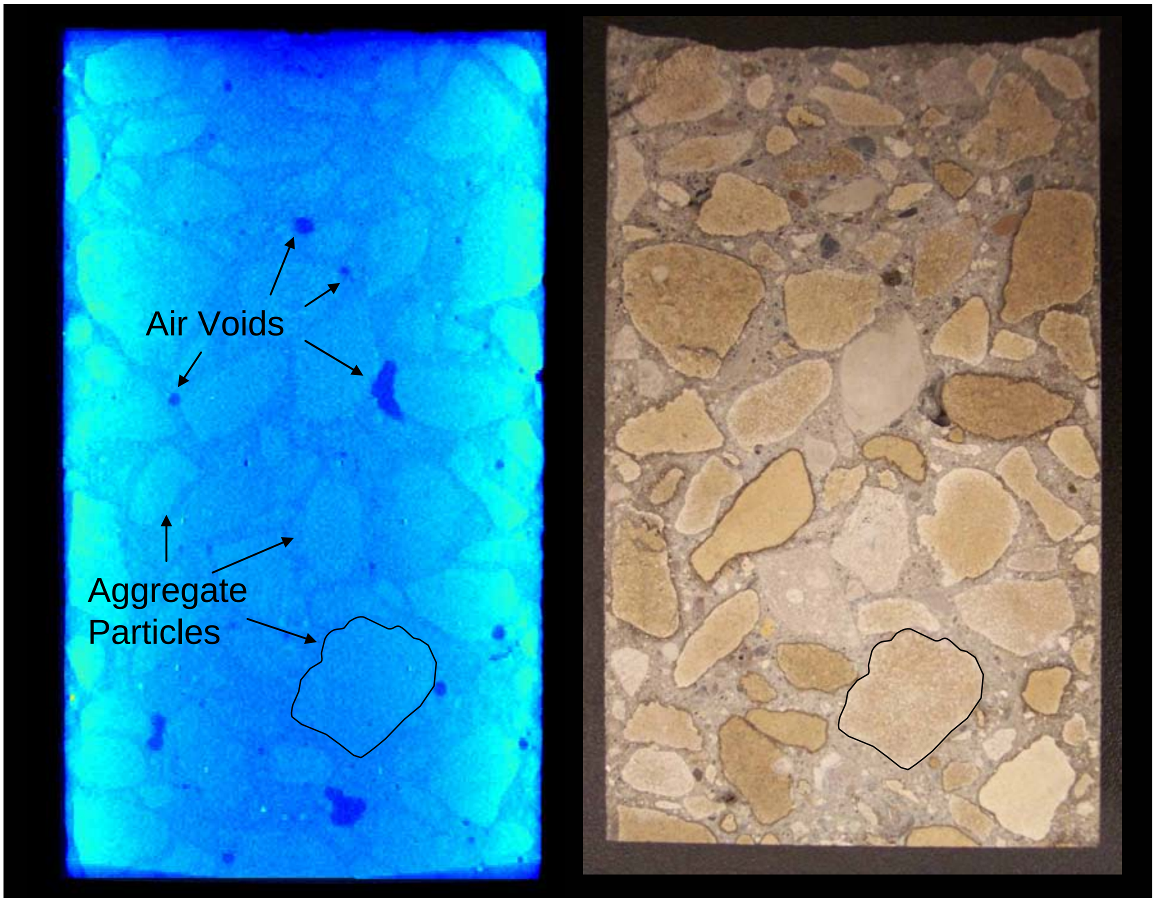


Figure 4.9. Sample one central profile, CT created (left) and actual saw cut (right)

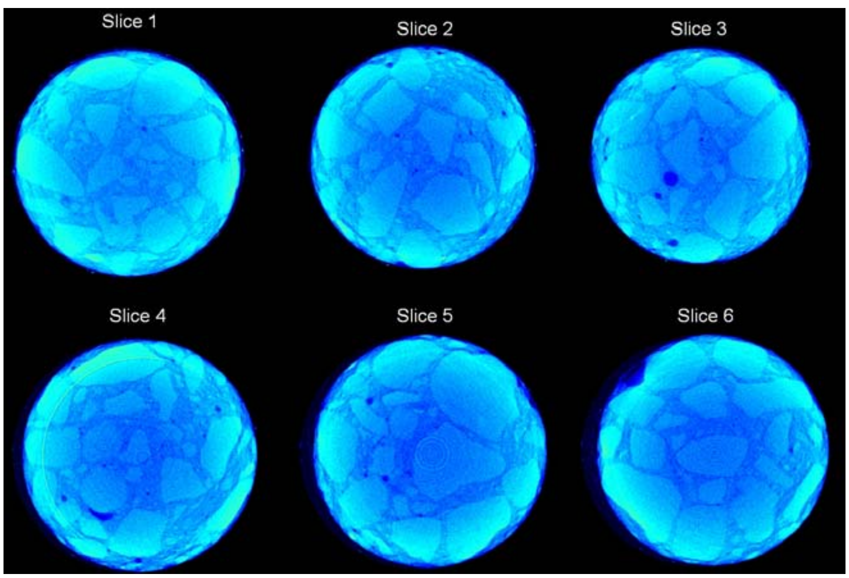


Figure 4.10. Sample two cross sectional slices

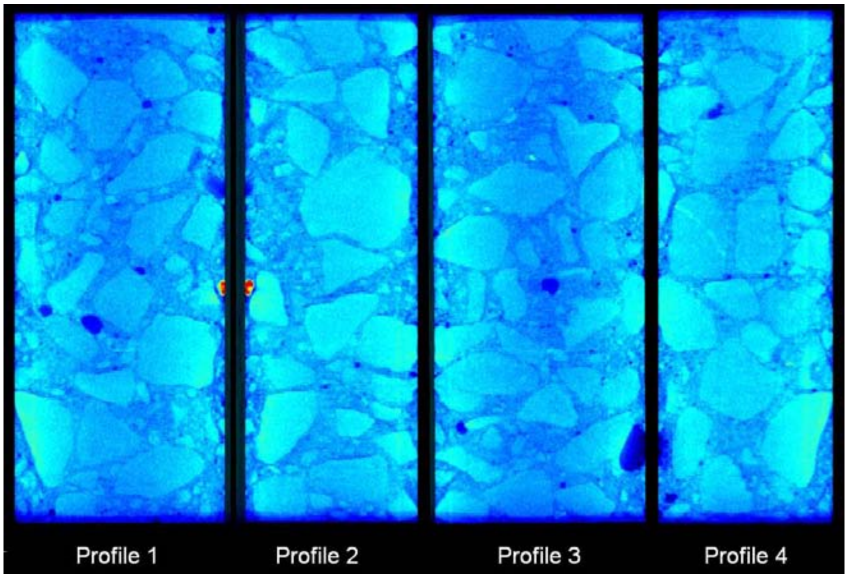


Figure 4.11. Sample two wrapping edge profiles

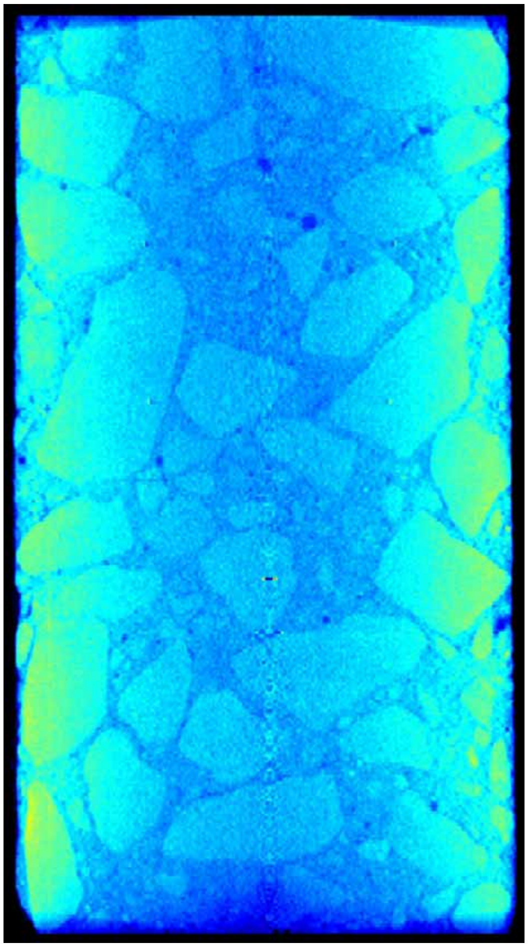


Figure 4.12. Sample two central profile

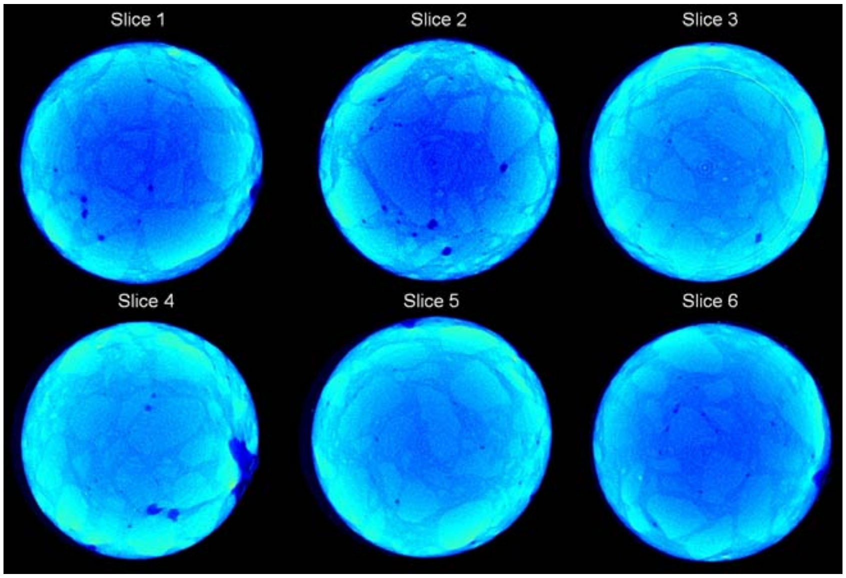


Figure 4.13. Sample three cross sectional slices

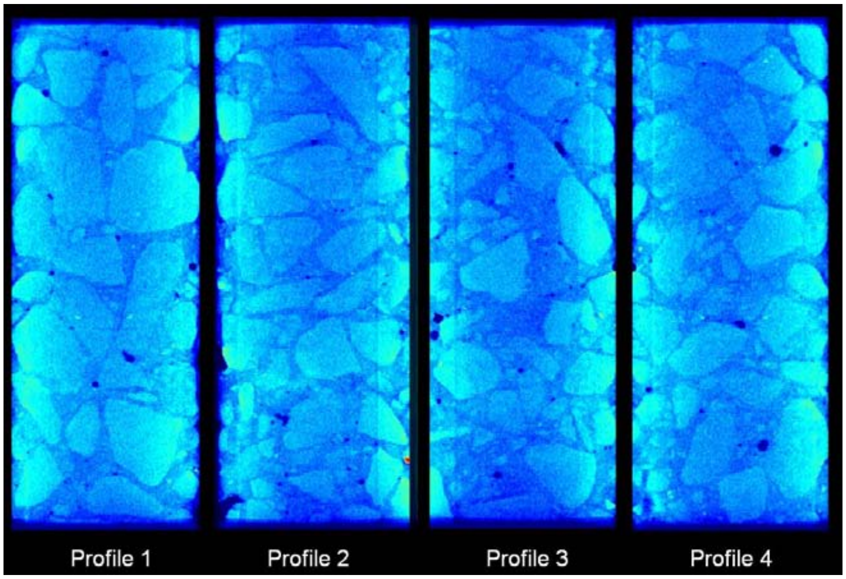


Figure 4.14. Sample three wrapping edge profiles

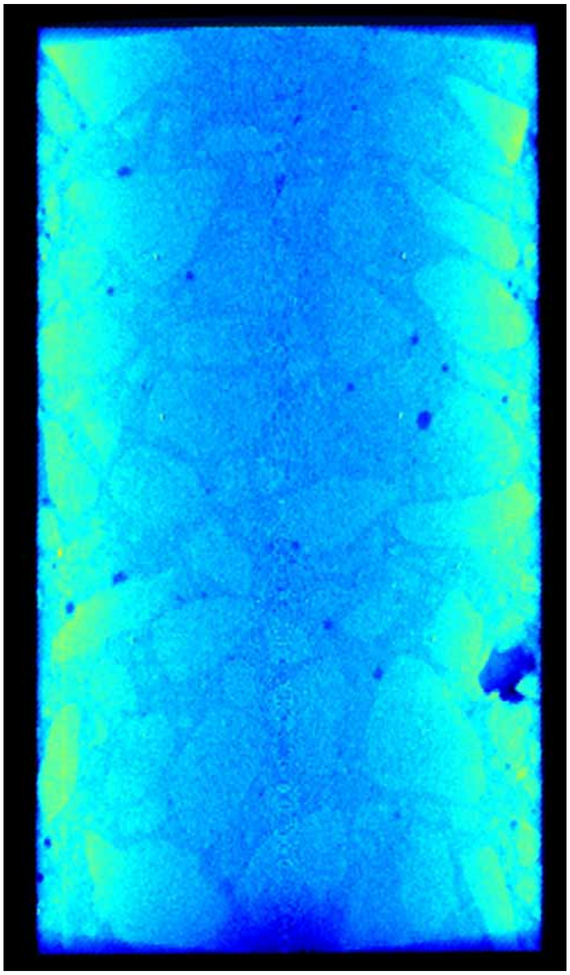


Figure 4.15. Sample three central profile

4.5. Conclusion

A self consolidating concrete mix created at Iowa State University was successfully scanned and analyzed using CT scanning hardware and software from the Center for Nondestructive Evaluation. Analysis results show that there are no large aggregates present in the top, central portion of two out of three samples analyzed. Two possible causes of the non-homogenous distribution are settlement over time and segregation caused by a 12-inch drop used to simulate field application.

It is recommended that in order to determine the cause of this effect, a field test plot could be constructed without using any drop height. If core samples reveal a lack of large aggregate at the top surface, then settlement is the most likely cause. If samples are homogenous then drop height is the most likely cause. However, both caused stem from aggregates being denser than surrounding cement.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Phase I Summary

In this study, a new type of self-consolidating concrete for slip-form paving (SF SCC) was developed. Effects of materials and mix proportions on fresh concrete compactibility, flowability, and shape stability were studied.

Type I cement, class C and F fly ashes, clay, and (meta) kaolin were used as cementitious materials. Air-entraining agent (AEA), viscosity modifying admixture (VMA), Acti-gel, and superplasticizer were employed as admixtures. Normal river sand and limestone were utilized as aggregate. Various concrete mix proportions were studied, and non-rodding slump flow test, modified compaction factor test, modified flow table test, rheometer test, and green strength tests were performed for the concrete mixtures. In addition, a mini-paver was developed to simulate the field SF SCC paving in laboratory.

The study has demonstrated that by engineering concrete materials and mix proportions, it is feasible to develop a new type of SCC for slip-form paving application. Concrete mixtures having a compaction factor of approximate 1.0, slump of approximated 8”, and spread of approximated 12” displayed not only to be able to self-compact but also to hold its shape right after placement. The test results also indicated that addition of fine particles and plasticizer could lead to significant improvement of the flowability of the fresh concrete. Despite having relatively high flowability, these mixes display very good shape stability in the fresh state. Addition of clay in concrete mixtures is also very effective in manipulating the shape stability of concrete.

In addition, X-ray computed tomography (X-ray CT) tests were also performed at ISU to monitor aggregate segregation and void distribution in selected SF SCC cylinder samples.

Another issue discussed by the research team and IAP members is the designation of the new slip-form concrete. The research team is searching for a name for the newly developed slip-form SCC so as to avoid the confusion between it and conventional SCC. Considering that the new concrete may require a minimum of compaction energy (such as a static pressure) to achieve a maximum density, the designations of “Minimally Compacted Concrete (MCC)” and “Minimal Compaction Energy Concrete (MCEC)” have been proposed. The term “SF SCC” is currently used in this document. More discussions will be held to finalize the designation.

5.2. Future Research

Although significant achievements have been made in Phase I, much more research on SF SCC still needs to be done because of the large variation of available concrete materials, pavements under different environmental conditions, and special requirements for concrete performance and durability. Considering the research results from Phase I and input from the IAP, the research team has modified the previous plan and set its priority for the following Phase II/III study tasks.

5.2.1. Phase II: Mix Design Refinement and Field Trial Testing of SF SCC

Task 1. Further Study SF SCC Materials and Mix Proportions

In Phase I, the research team developed several promising mixture proportions for potential field application of SF SCC. This work will be extended with additional study on the concrete mix design in this Phase II task. Because of the limited time in Phase I, systematical study on various material and mix-design variables has not been completed. These variables shall include different type, size, and gradation of aggregate, different type and proportion of cementitious materials (portland cement, fly ash, slag, silica fume, and clay), and different type and amount of chemical admixtures (water reducer, superplasticizer, VMA, and Acti-Gel). In particular, the low additive amounts of Acti-Gel will be studied, and the combined effects among different plasticizers, cement or aggregate content, and Acti-Gel content will be investigated.

A mix design matrix will be developed using a statistical design method. The matrix will cover the types and ranges of material components of SF SCC. A rational minimum number of mixes will be selected from the matrix, and screening tests will be performed to find out how the designed parameters influence flow properties, shape-holding ability, green strength, and hardened strength of the SCC mixes. Refined mix proportions shall be proposed for Phase III based on the test results.

Task 2. Conduct Quality Control Tests for Selected SF SCC Mixtures

In addition to slump and green strength, set time, heat of cement hydration, or maturity, entrained and entrapped air content, and 1-day compressive strength of concrete will be tested for selected SF SCC mixes. These tests will provide engineers with basic information on fresh concrete performance and on the time for saw cutting and/or the time for pavement to open to traffic. It is also necessary to develop appropriate test methods and test criteria for SF SCC.

Task 3. Investigate Engineering Properties and Durability of the SF SCC Candidates for Phase III

Based on the analysis of test data obtained from Tasks 1 and 2, two to three potential SF SCC mix proportions will be selected and recommended for Phase 3 field investigation. In the consideration that the new Mechanistic-Empirical Pavement Design Guide (MEPDG) requires various input parameters, the engineering properties and durability (such as elastic modulus, Poisson ratios, thermal coefficient, shrinkage resistance, freezing-thawing resistance, etc.) of the SF SCC candidates will be studied. Since the materials used in SF SCC are similar to those of conventional SCC, alkali-silica reaction (ASR) shall not be a particular problem; and therefore ASR in SF SCC can be studied later.

Task 4. Conduct Field Paving Trial Tests Using SF SCC

During Phase I, the research team and IAP members recognized and discussed the scale problem related to the lab simulation conducted with the mini-paver. Although the current mini-paver can pave a slab with a thickness varying from 3” to 6”, the lab paving situation is still very different from that of 8”–12” thick concrete paving in the field. Depending on mix design, the SF SCC shape-holding ability may be significantly affected by the pavement geometry (such as height). Therefore, mini-field tests are proposed before the SF SCC is applied to full-scale field paving. One or two field trial tests can be performed for paving of curb, bike-trail, or whitetopping using the newly developed SF SCC.

Task 5. Develop SF SCC Mix Design Methodology and Acceptance Criteria

Besides identifying a few of promising SF SCC mix proportions, the objective of this task is to develop a methodology for SF SCC mix design. One methodology for conventional SCC mix design is to divide the concrete into two constituents: coarse aggregate and mortar. The rheology of the mortar is adjusted to achieve self-flowing concrete via incorporation of a variety of mineral additives, plasticizers, and thickeners. This methodology can be modified in consideration of aggregate-packing density and then be used for the present research.

ACBM has developed a rheological model that makes possible the close control of SCC properties while the construction project suffers changes of raw materials and climatic conditions. This model is a tool for mix design, choice of materials, and quality control, as well as for enabling further developments of admixtures and additives for SCC. The model is based on paste rheology criteria, which includes minimum apparent viscosity, minimum flow, and optimum flow-viscosity ratio to achieve SCC with satisfactory segregation resistance and deformability.

The rheological criteria of the cement paste matrix are related to the average aggregate diameter and aggregate spacing, which are both influenced by the physical properties and total aggregate content of the concrete. The properties of SCC are characterized by quantitative measures of segregation and flow.

Because the previously developed mix design criteria for conventional SCC cannot be directly applied to the new SF SCC, the existing criteria for conventional SCC will be modified and new criteria for SF SCC mix design will be established according to the preliminary information obtained from Tasks 1–3. To achieve this, the optimal combination of yield stress and viscosity for SF SCC will be determined.

Task 6. Further Study the Green Strength, Shape-holding Ability, and Compactibility of SF SCC

Research has revealed that the distance between aggregate surfaces dominates concrete particle packing, which has considerable influence on the concrete flow properties. Factors such as aggregate size, shape, content, gradation, and coarse aggregate/total aggregate ratio affect the spacing between aggregate particles in concrete. Green strength of SCC provided by internal friction and cohesion also significantly depends on the aggregate (or paste) volume and particle arrangement/orientation. In the proposed research, the internal friction and cohesion of SF SCC aggregate particles will be studied using a direct shear test based on the concept of soil mechanics, and the aggregate packing characteristics will be studied using X-ray CT scanning. X-ray CT scanning equipment is available at the Center for Nondestructive Evaluation (CNDE) at ISU. By using this technology, particle packing characteristics of current pavement concrete and newly developed SCC mixes will be further studied, and their effects on flowability, stability, and green strength of concrete will be investigated.

The previous research has shown that the desired properties of SF SCC can only be accomplished if the parameters of green strength and flowability are located within a certain range. For most of the tested mixtures, these two parameters follow a trend that shows a decrease in green strength with an increase in flowability. However, some of the tested mixtures do not follow this trend and they have higher green strength for a given flowability. An important objective of the next research phase is to understand the factors that govern the relationship between green strength and flowability of fresh concrete. These investigations will also include a third parameter—the void content of the concrete after the compaction. The optimum combination of these three parameters (green strength, flowability, and void content) will yield concrete mixtures that perform best for the desired slip-form paving application.

The researchers will continue finding appropriate ways to characterize the compactibility and flowability of fresh concrete. The flow drop table tests used in Phase I can be further employed to conduct reliable and repeatable tests on concrete with small size aggregates. To investigate concrete with the large size limestone aggregates, a new, large-scale, drop table test will be devised. This test will allow a rapid assessment of the flowability of any concrete mixture in laboratory as well as in the field.

Phase I study has indicated that pressure has significant influence on concrete shape-holding ability. In Phase II, emphasis will be placed on the development of a laboratory compactibility test of fresh concrete using a hydraulic test machine (see Figure 5.1). This type of test is necessary to work with concrete containing large sized aggregates. This test yields the relationship between applied compaction energy (vertical static force) and resulting compaction of the test material. First results that have been obtained with the test setup have proven the applicability of the test method to characterize fresh concrete mixtures. The test method will be used to transfer the knowledge derived from the experiments with small sized aggregates to the mixtures with large lime stone aggregates.

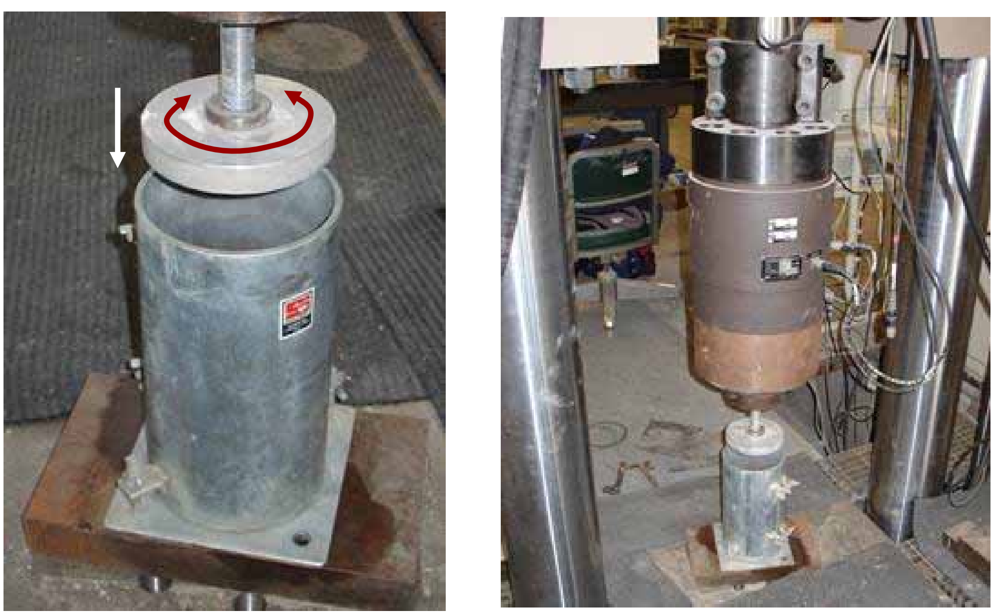


Figure 5.1. Test setup for determining the compactibility of fresh concrete by using a hydraulic test machine

5.2.2. Phase III: Field Investigation of SF SCC Paving, Performance Monitoring of SF SCC Pavement, and Technology Transfer of the Project Results

Phase III will include a field study (Phase IIIA) and performance monitoring and technology transfer (Phase IIIB).

<u>Phase IIIA. Field Study</u>

The following tasks are recommended for Phase IIIA study of this research project:

- Examine current paving equipment for possible need of modification for SF SCC application.
- Select construction time and location.
- Establish primary guidelines for construction of SF SCC, including modification of the existing slip-form paver for the SCC paving.
- Develop field test methods for data collection.
- Perform field tests.
- Analyze field test data.

Details for the tasks will be developed by the project investigators based on the research results from Phase II and the input from the IAP members at the end of Phase II.

The final project report, including research activities and results of Phases I–IIIA, will be developed at the end of Phase IIIA.

<u>Phase IIIB. Performance Monitoring and Technology Transfer</u>

As part of Phase IIIB, in-service performance of the field demonstration sites will be monitored and documented in supplemental reports at 1-, 3-, and 5-year intervals. The pavement performance characteristics to be monitored and/or evaluated will include pavement surface condition (such as smoothness, cracking, and surface defects), concrete strength, air voids characteristics, and structural integrity. Non-destructive evaluation (NDE) methods such as laser scan and falling weight deflectometer (FWD) may be used in addition to visual examination. Cores may be taken from selected area for strength and air void analysis.

5.3. Anticipated Project Impact and Implementation

5.3.1 Implementation Plan

- DOTs may conduct demonstration projects for the implementation of pavement system design and construction using SF SCC.
- DOTs, together with construction equipment companies, may modify existing pavers to fit the new paving technology.
- Long-term properties, especially durability, of the new SF SCC should be further studied and the field SCC performance should be monitored.

- DOT council action may include the development of new specifications for design and construction of SF SCC.

5.3.2. Implementation Benefits

The research results will be used not only for paving but also for slip-form construction of pipes, tanks, towers, silos, and high-rise buildings. There should also be a specification developed that addresses pavement structure design, material design, and construction of SF SCC. Construction equipment will be modified (simplified) based on the new paving technology.

This new technology will have a revolutionary impact on the environment, construction costs, and pavement sustainability. The potential benefits of having such a new type of SF SCC include the following:

- Eliminate the vibrator trails in concrete pavement and improve pavement durability.
- Enhance the quality, especially the uniformity, of concrete pavements by reducing the problems resulting from inconsistent vibration of concrete.
- Improve pavement smoothness with minimum surface finishing requirements.
- Expedite construction speed and reduce construction energy and noise that are consumed and generated by vibrator.
- Overcome some construction difficulties in the concrete and pavement constructions (such as ultrathin overlay, two-lift, and curb paving) where a regular vibration may hardly be applied properly.
- Moderate the hydraulic pressures generated from and heavy formwork required by the use of conventional SCC.

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